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Specification for a Standard Electromagnetic Propagation Model

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ADMINISTRATIVE INFORMATION

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1.0 INTRODUCTION

A standard electromagnetic (EM) propagation model has been developed at the Naval Ocean Systems Center. It provides the user with a method of assessing EM propagation from 100 MHz to 20 GHz in the marine environment for a variety of atmospheric conditions. The software implementation of the model returns the pattern propagation factor in decibels when a user supplies the model with the proper environmental and EM system inputs. The pattern propagation factor is defined as the ratio of the actual electric field at some point to the field that would exist at that point under free-space propagation conditions. Free-space propagation is the propagation of energy that would occur if an omnidirectional point-radiating source were placed in outer space. The radiated energy would travel outward in all directions, the wave fronts propagating away from the source with the same velocity in all directions. Obviously these conditions would not be satisfied if the point source was placed in the near-earth environment. Refraction by the atmosphere ensures that the energy is not propagated with the same velocity in all directions, and the surface of the earth can intercept and reflect some portion of the energy. If the functional form of the pattern propagation factor is known, then the propagation loss is known, since the calculation of the free-space loss is simple. The pattern propagation factor is also useful because it appears in the radar-range equation and can be used to assess radar system performance. The model is described in this report in detail and an ANSI Fortran program using the model is provided. The program that implements the model can be either incorporated into an application model that requires EM propagation information or used as a stand-alone program.

2.0 INPUTS, OUTPUTS, AND LIMITS

2.1 INPUTS

A number of EM system and environmental inputs are required to determine the pattern propagation factor. The necessary EM system parameters are given in Table 2-1. The required environmental inputs are provided in Table 2-2. The antenna beamwidth and elevation angle parameters of Table 2-1 are not required for an omnidirectional antenna type.

Table 2-1. Required EM system inputs.

Parameter	Units	Valid Input Range
Frequency	MHz	100.0 to 20,000.0
Height of Transmitting Antenna	m	1.0 to 100.0
Radar Target/Receiver Antenna Height	m	1.0 to 30000.0
Transmitting Antenna Polarization	n/a	Horizontal, vertical or circular
Transmitting Antenna Type	n/a	Omnidirectional, sin $(x)/x$ cosecant-squared, height-finder, specific system height-finder
Antenna Beamwidth	deg	>0 to 45.0
Antenna Elevation Angle	deg	-10.0 to 10.0
Range	km	1 to 1000.0

Table 2-2. Required environmental inputs.

Parameter	Units	Valid Input Range
Evaporation Duct Height	m	0.0 to 40.0
Surface Wind Speed	kt	0.0 to 50.0
Height Array — 2 to 30 Elements	m	0.0 to 10000.0
M-unit Array — Each Element Corresponding to the Like-Number Height Array Element	M	0.0 to 2000.0

2.2 OUTPUTS

The only output is the calculated pattern propagation factor (in decibels) for the specified inputs of Tables 2-1 and 2-2. Sample program outputs for a variety of environmental and EM system inputs are presented in Section 4.0.

2.3 LIMITS

The standard propagation model described in this document will return a value of the pattern propagation factor in decibels for EM system operational parameters within the range of validity of the inputs of Table 2-1 and for environmental inputs within the range of validity of Table 2-2.

3.0 STANDARD PROPAGATION MODEL

The simplest case of electromagnetic wave propagation is the transmission of a wave between a transmitter and a receiver in free space. Free space is defined as a region whose properties are isotropic, homogeneous, and loss-free, i.e., away from the influences of the earth's atmosphere. In free space, the electromagnetic wave front spreads uniformly in all directions from the transmitter.

While the total amount of energy transmitted does not vary, i.e., no losses to absorption, etc., the energy is distributed over an ever-enlarging surface. Thus the energy level along any one ray decreases inversely with the square of the sphere's radius. This is called the *free-space path loss*. The free-space path loss for isotropic antennas, expressed in terms of frequency, is

$$L_{fs} = 32.44 + 20 \log(r) + 20 \log(f) \qquad (1)$$

for r in kilometers and f in megahertz.

If nonisotropic antenna radiational patterns are considered within the loss calculations, the los is referred to as *propagation loss* rather than path loss. The propagation loss can be described with the aid of the *pattern propagation factor*, which is defined as the ratio of the actual field strength at a point in space to the field strength that would exist at the same range under free-space conditions with the beam of the transmitter directed toward the point in question. For simplicity, the term *propagation factor* is used throughout this document to refer to the pattern propagation factor. Thus, the effects of the transmitter antenna pattern are implied in all calculations. Symbolically the propagation factor, F, is given by

$$F = \frac{|E|}{|E_o|} \qquad (2)$$

where E_o is the magnitude of the electric field under free-space conditions and E is the magnitude of the field to be investigated at the same point.

The propagation factor is a desirable quantity, since it is an identifiable parameter in most radar-detection-range equations. It contains all the information necessary to account for such effects as sea-surface reflection, atmospheric refraction, scattering from inhomogeneities in the atmosphere and diffraction from the bulge of the earth's surface. Thus, if the functional form of F is known, then the propagation loss at any point can be determined, since the calculation of the free-space field is quite simple. The propagation loss (in decibels), including antenna patterns, is equivalent to

$$L = L_{fs} - 20 \log(F) \qquad (3)$$

Three regions require different methods for obtaining signal strength (or, equivalently, propagation factor or loss) as a function of range. The first region is called the optical interference, or optical, region and extends roughly from the transmitter to the radio horizon. In the optical region, propagation is dominated by two-path coherent interference between direct and surface-reflected waves. The other distinct region is the diffraction/troposcatter region, which begins just beyond the radio horizon. A third region, called the intermediate region, lies between the optical and the diffraction region. The propagation factor in this region is obtained by a linear interpolation between F values in the optical and diffraction regions.

The standard propagation model that will be presented here assumes a single-layer atmosphere. The assumption of a single-gradient atmosphere is somewhat restrictive, since nature does not always provide such a simple propagation medium. The basic assumption of the single-layer model is that refraction can be treated by assuming that the refractive bending of the EM rays can be accounted for by using an *effective earth radius* that is different (usually larger) than the true earth radius. Ray paths over such an earth would then appear to be straight lines rather than curved paths. To obtain an equivalent single-gradient atmosphere from an arbitrary one, a ray trace must be used. A ray is traced from the transmitter height to some arbitrarily distant point through the various atmospheric layers. The height at this range is then used to determine the equivalent single-gradient atmosphere that would be required to trace a ray to this range and height. This equivalent gradient is used to define an *effective earth radius* factor. The procedure is explained in more detail in Section 3.1.4.

In the discussion of the models, all heights are in meters, all ranges are in kilometers, and all angles are in radians unless specifically stated otherwise.

3.1 OPTICAL INTERFERENCE REGION MODELS

For naval EM systems operated near the earth's surface, the electric field at a receiving antenna or radar target is the vector sum of the field components which arrive at that point via the direct and sea-reflected paths, as shown in Fig. 3-1. The phase component of the reflected ray will lag the phase of the direct path because of the difference in path lengths. The total phase lag, Θ, is given by

$$\Theta = \delta + \Phi \tag{4}$$

where δ is the path-length difference and Φ is the phase change caused by reflection from the surface. Here the assumption is made that the direct and sea-reflected rays have very nearly the same spatial direction, so that the major factor in their addition is the phase difference. Kerr (1951) gives the following expression for F in the absence of abnormal absorption or refractive effects:

$$F = \{f(\epsilon_1)^2 + [f(\epsilon_2)\, D\, R]^2 + 2\, D\, R f(\epsilon_1) f(\epsilon_2) \cos(\Theta)\}^{1/2} \tag{5}$$

The $f(\epsilon_i)$ factors describe the (normalized to 1) antenna pattern, and the angles, ϵ_i, are shown in Fig. 3-1. D is called the divergence factor and takes into account the spherical nature of the reflecting surface. R is the reflection coefficient of the reflecting surface (the ratio of the magnitudes of the reflected and incident fields). F varies from maximum to minimum as the total phase lag, Θ, changes by π and can assume values between 0 and 2.

The path-length difference, δ, in radians, between the direct and reflected rays is given by

$$\delta = (4.193 f H_t' H_r' 10^{-5})/r \tag{6}$$

Here r is the total ground range, and H_t' and H_r' the effective antenna heights. H_t' and H_r' are shown in Fig. 3-1 and are given by

$$H_t' = H_t' - (1000\, r_1^2)/(2\, a_e) \qquad \text{(m)} \tag{7}$$

$$H_r' = H_r' - (1000\, r_2^2)/(2\, a_e) \qquad \text{(m)} \tag{8}$$

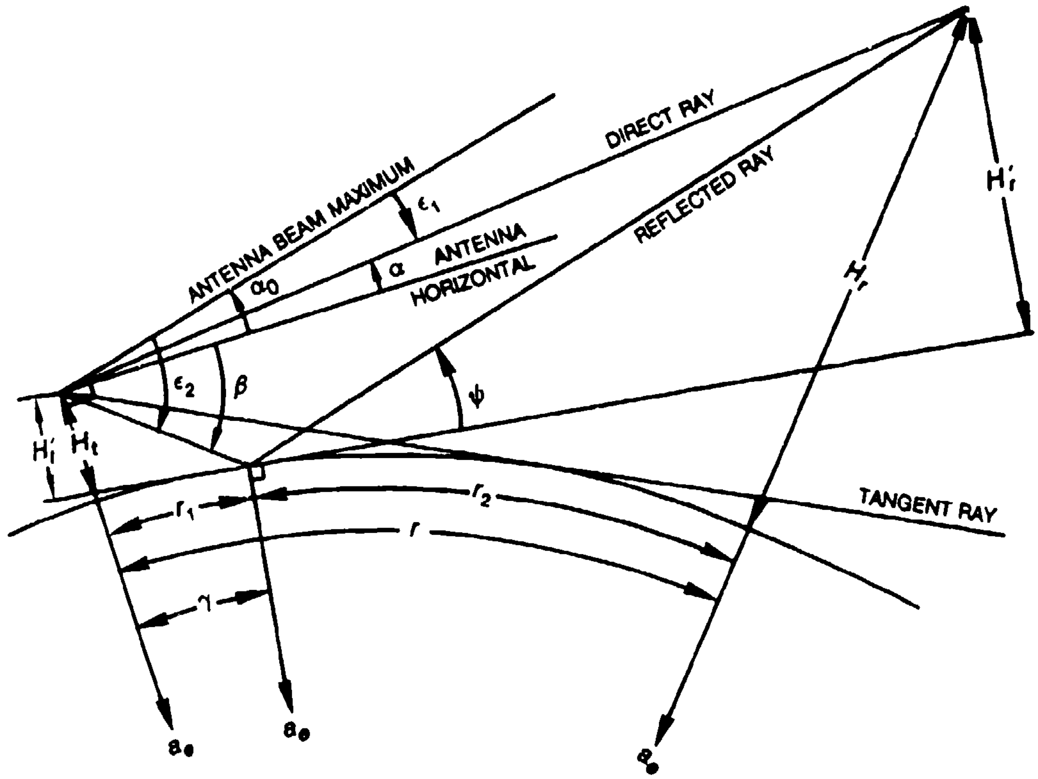

Figure 3-1. Two-path optical interference region.

where H_t and H_r are the transmitter and receiver/target heights, respectively. a_e is the effective earth radius which is defined as the effective earth radius factor, k, times the mean earth radius of 6371 km. r_1 and r_2 are the reflection point ranges. r_1 can be determined by solving the cubic equation

$$2r_1^3 - 3rr_1^2 + [r^2 - 0.002\,a_e(H_t + H_r)]r_1 + 0.002\,a_e H_t r = 0 \tag{9}$$

This equation is frequently solved by using a Newton-method iterative technique, but also has the following formal solution when $H_r \geq H_t$:

$$r_1 = r/2 - p\cos[(\xi + \pi)/3] \tag{10}$$

where

$$p = \{(4/3)[0.001\,a_e(H_t + H_r) + (r/2)^2]\}^{1/2} \tag{11}$$

and

$$\xi = \cos^{-1}\{[0.002\,a_e(H_r + H_t)r]/p^3\} \tag{12}$$

The antenna pattern factors, $f(\epsilon_i)$, require angular information about the angles α and β, as shown in Fig. 3-1. The magnitude, R, and phase shift, Φ, require knowledge of the grazing angle, ψ. These angles, in radians, are

$$\alpha = 0.001\,(H_r - H_t)/r - r/(2\,a_e) \tag{13}$$

$$\psi = 0.001\,H_t'/r_1 \tag{14}$$

$$\gamma = r_1/a_e \tag{15}$$

$$\beta = -\gamma - \psi \tag{16}$$

in terms of the variables shown in Fig. 3-1. The divergence factor can be calculated by using the equation

$$D = [1 + (2\,r_1\,r_2)/(r\,a_e\,\psi)]^{1/2} \tag{17}$$

Because Eq. 9 only applies for $H_r \geq H_t$, these terminal heights are normally swapped if $H_r < H_t$, for the calculation of r_1 only. Equation 13 will give correct values of α for the antenna pattern calculations if the true (unswapped) values of H_t and H_r are used in this calculation. However, r_1 in Eq. 15 must be replaced with r_2 to obtain the correct antenna pattern factor for the reflected ray if the terminal heights have been swapped.

3.1.1 Reflection Coefficient Models

The magnitude and phase shift of the reflected ray can be calculated as a function of the grazing angle, ψ. The magnitude, R, and the phase shift, Φ, of the reflected ray for horizontal and vertical polarizations, respectively, are

$$R_H = 1 \tag{18}$$

$$\Phi_H = \pi \tag{19}$$

$$R_V^{i\Phi_V} = \frac{n^2 \sin(\psi) - [n^2 - \cos^2(\psi)]^{1/2}}{n^2 \sin(\psi) + [n^2 - \cos^2(\psi)]^{1/2}} \tag{20}$$

where n is the (complex) index of refraction and the subscripts H and V indicate the polarization. The reflection coefficient for circular polarization, calculated in terms of the horizontal and vertical coefficients, is

$$R_C = 0.5\,[R_V^2 + R_H^2 + 2R_V R_H \cos(\Phi_H - \Phi_V)]^{1/2} \tag{21}$$

$$\Phi_C = \Phi_H - \sin^{-1}[R_V \sin(\Phi_H + \Phi_V)/(2\;R_C)] \tag{22}$$

The magnitude of the reflected ray is also affected by the roughness of the reflecting surface. Surface roughness is included following the models of Ament (1953), Beard (1961), and Barrick (1971) by using the formulas

$$R = R_o \exp(-2\{[2\pi h \sin(\psi)]/\lambda\}^2) \qquad (h\psi)/\lambda < 0.110 \qquad (23)$$

$$R = R_o (0.5018913 - \{0.2090248 - [(h\psi)/\lambda] - 0.55819\}^2)^{1/2}$$
$$0.110 \le (h\psi)/\lambda \le 0.260 \qquad (24)$$

$$R = 0.15\, R_o \qquad (h\psi)/\lambda > 0.260 \qquad (25)$$

where R_o is the reflection coefficient for a smooth surface, h is the root-mean-squared (rms) wave height, and γ is the wavelength. The rms wave height is obtained as a function of wind speed by using the Phillips (1966) ocean-wave model

$$h = 0.0051\, W_s^2 \qquad (26)$$

for wind speed (W_s) in m/s.

The square of the index of refraction required to make the calculation of R and Φ for vertical and circular polarizations is given by

$$n^2 = \epsilon - i\,(18{,}000\,\sigma)/f \qquad (27)$$

where ϵ and σ are the ordinary dielectric constant and conductivity, respectively, of seawater, and f is the EM system frequency in megahertz. The constants themselves are obtained as a function of frequency by using Blake's (1970) equations, as follows:

Case 1: $f \le 1500$

$$\epsilon = 80 \qquad (28)$$

$$\sigma = 4.3 \qquad (29)$$

Case 2: $1500 < f \le 3000$

$$\epsilon = 80 - 0.00733(f - 1500) \qquad (30)$$

$$\sigma = 4.3 + 0.00148(f - 1500) \qquad (31)$$

Case 3: $3000 < f \le 10{,}000$

$$\epsilon = 69 - 0.00243(f - 3000) \qquad (32)$$

$$\sigma = 6.52 + 0.001314(f - 3000) \qquad (33)$$

For frequencies greater than 10,000 MHz, the 10,000 MHz values are used.

3.1.2 Antenna Pattern Factor Models

The remaining terms in Eq. 5, $f(\epsilon_i)$, the normalized antenna pattern factors, are determined as a function of the antenna pattern type, beamwidth, and pointing angle. Five different antenna types can be used: omnidirectional, sin $(x)/x$, cosecant-squared, generic height-finder, and specific system height-finder. The specific system height-finder antenna type is not discussed here. Antenna patterns for these antennas can be implemented by replacing the antenna pattern functions with user-supplied data. The simplest case is that of the omnidirectional antenna which, as its name implies, has a gain of unity in all directions. That is, $f(\mu) = 1$ for all angles μ.

The second case is the sin $(x)/x$ antenna type. The radiation pattern of this antenna is symmetric about the elevation (pointing) angle of the antenna. The pattern factor for this antenna is given by Blake (1970) as

$$f(\mu) = \sin(x)/x \qquad f(\mu) \geq 0.03, \qquad -\mu_{max} \leq \mu \leq \mu_{max} \tag{34}$$

where

$$x = c \sin(\mu - \mu_0) \tag{35}$$

and μ_0 and μ_{max} are the elevation angle and maximum angle in the main beam, respectively. The value of c is chosen so that $f(\mu) = 0.7071$ when $\mu = \mu_0 \pm BW/2$, where BW is the beamwidth. This normalization ensures that the antenna half-power points $\{20 \log [f(\mu)] = -3 \text{ dB}\}$ occur at $\mu = \mu_0 \pm BW/2$, which is the usual definition of the beamwidth of the antenna. That is

$$c = 1.39157/\sin(BW/2) \tag{36}$$

Pattern factor calculations are limited to those angles within the main beam of the antenna down to the -30 dB level $[f(\mu) \geq 0.03]$. Angles greater than

$$\mu_{max} = \mu_0 \pm \tan^{-1}[A/(1 + A)]^{1/2} \tag{37}$$

where $A = \pi/c$, are limited to a pattern factor of 0.03. This is equivalent to an antenna with its first sidelobes at -30 dB, a condition easily achieved with modern antennas.

The generic height-finder antenna is a special case of the sin $(x)/x$ antenna. Height-finder antennas typically sweep the beam upward in elevatirn. This can be simulated by substituting the direct ray angle, μ, for the elevation angle, μ_0. Then $f(\mu) = 1$ for all values, μ, of the direct ray set. As the antenna beam is swept upward, the pattern factor for the reflected ray gradually tapers to the -30 dB level.

A fourth antenna type is the cosecant-squared antenna. This antenna pattern is not symmetric about the elevation angle. The pattern factor is calculated by using

$$f(\mu) = 1 \qquad \mu_0 \leq \mu \leq \mu_0 + BW \tag{38}$$

$$f(\mu) = \sin(BW)/\sin(\mu) \qquad \mu > \mu_0 + BW \tag{39}$$

$$f(\mu) = [1 - (\mu_0 - \mu)/BW] \qquad f(\mu) \geq 0.03, \qquad \mu < \mu_0 \tag{40}$$

This antenna pattern is different from the sin $(x)/x$ antenna, since the beamwidth of this antenna does not coincide with the -3 dB, or half-power, points of the antenna. The orientation of the antenna given above is the one that would be used for shipboard radars. Cosecant-squared antennas used on an airborne radar are normally oriented in the reverse sense so that the first two equations above would describe the direct ray angles below the elevation angle μ_0. The third equation would then describe the beam taper above the elevation angle. The antenna orientation is not optional, and the antenna is always assumed to be that of a surface-based system.

3.1.3 Ray Trace Models

The standard propagation model obtains the required value of the effective earth radius factor, k, by means of a ray trace. The model allows the user to input an M-unit-versus-height profile, which is used in performing the ray trace. The ray trace equations are based on small-angle approximations to Snell's law and on the assumption of a linear variation of modified refractivity, M, with height up to 30 vertical segments. The trace of an individual ray begins with an elevation angle specified at some initial height and range and consists of a series of calculations to determine a series of height and range points along the ray trajectory. The M-unit profile is constructed so that the M-unit value at the surface and a zero-meter height are the first elements in the profile arrays. The remainder of the M-unit profile has a height array of ascending heights, in meters, and an M-unit array with the corresponding M-unit value in a like-numbered array. A third array can be constructed from these two arrays which contains the gradient between adjacent layers. The general definition for this array is

$$dMdh_i = 10^{-3}(M_{i+1} - M_i)/(H_{i+1} - H_i) \tag{41}$$

where M_j denotes the M-unit array and H_j the height array elements, respectively. Negative values of $dMdh_i$ indicate trapping layers. A standard atmosphere (4/3 earth) gradient is usually defined for the gradient above the highest height array element, that is, $dMdh_k = 0.000118$, where k is the index of the last element in the H array. $dMdh$ values of zero are not allowed, which is equivalent to not allowing the M-unit values of adjacent height values to be equal.

A critical launch angle can be determined for transmitter heights within ducts. This critical angle is defined as the minimum positive launch angle *not* trapped in the duct. The positive critical angle is given by

$$\alpha_c = 10^{-3}[2(M_{H_t} - M_{min})]^{1/2} + 10^{-5} \tag{42}$$

while the minimum negative critical angle is equal to $-\alpha_c$. Here M_{H_t} is the M-unit value at the transmitter and M_{min} is the minimum M-unit value at some height greater than H_t. If H_t is in a duct, then the duct is treated as a surface-based duct even if it does not extend to the surface. The height where M_{min} occurs is the height of the surface-based duct. H_t must be in the the duct for Eq. 42 to be valid, though if H_t is above the duct, $-\alpha_c$ would define the launch angle for a ray tangent to the top of the duct at some range. Rays launched with angles $\alpha_c > \alpha > -\alpha_c$ will be trapped within the duct.

The general ray trace equations using the H, M, and $dMdh$ arrays can be divided into three categories: rays with the terminal range known, rays with the terminal height known, and rays with the terminal elevation angle known. Figure 3-2 illustrates a ray with a positive launch angle, but the equations also apply to negative launch angles when proper attention is paid to the layer indices and

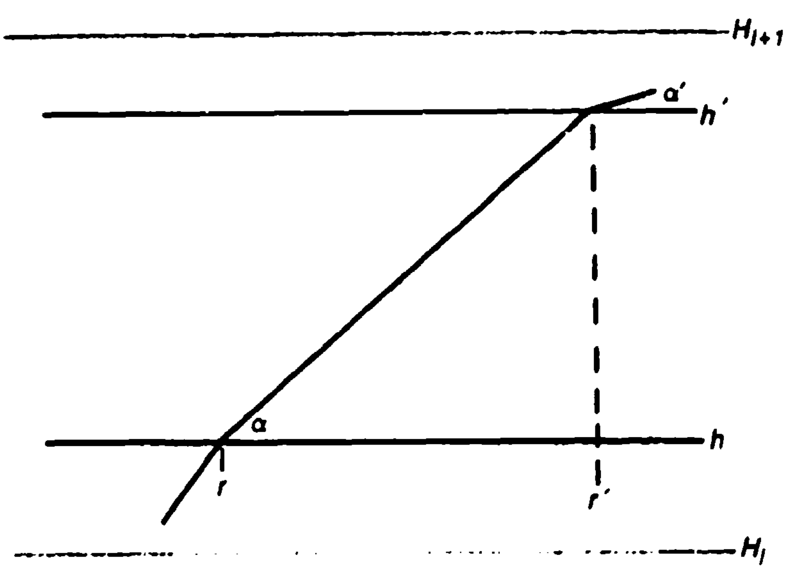

Figure 3-2. Ray trace variables.

sign of the launch angle. The equations given apply only to range and height values within individual layers. All heights are in meters and ranges in kilometers.

Case 1: h' known, $\alpha \neq 0$

$$\alpha' = [\alpha^2 + 0.002\, dMdh_l\,(h' - h)]^{1/2} \tag{43}$$

$$r' = r + (\alpha' - \alpha)/dMdh_l \tag{44}$$

Case 2: r' known, $\alpha \neq 0$

$$\alpha' = \alpha + dMdh_l\,(r' - r) \tag{45}$$

$$h' = h + (\alpha'^2 - \alpha^2)/(0.002\, dMdh_l) \tag{46}$$

Case 3: α' known

$$r' = r + (\alpha' - \alpha)/dMdh_l \tag{47}$$

$$h' = h + (\alpha'^2 - \alpha^2)/(0.002\, dMdh_l) \tag{48}$$

If the radicand of Eq. 43 is negative, there is no solution for the given height, h', since the ray has reached a maximum (or, in the case of a downgoing ray, a minimum) height less (or greater) than h'. In this case, the range and height of the ray maximum (minimum) are given by

$$r' = r - \alpha/dMdh_l \tag{49}$$

$$h' = h - \alpha^2/(0.002\, dMdh_l) \tag{50}$$

while $\alpha' = 0$ at this range and height. One unique case not covered by the above equations is the special case $\alpha = 0$. In this case, if $dMdh_i > 0$, the ray will become an upgoing ray; if $dMdh_i < 0$, the ray will become a downgoing ray. Equations 43 through 50 can be iteratively used to trace ray paths through the user-specified stratified atmosphere.

3.1.4 Effective Earth Radius Model

The ray trace equations are used to trace a ray through the specified atmosphere to determine the value of the effective earth radius factor, k, since k is only defined for a single-layer atmosphere. A ray with a launch angle $\alpha = 0$, or $\alpha = \alpha_c$ if the transmitter is in a duct, is traced to 370 km (200 nmi). The ray height at that range is compared to the height a ray would reach in a standard atmosphere to calculate a value of k. The single-layer equivalent M-unit gradient is given by

$$Q = -(2\alpha)/370 + (0.002\ \Delta H)/(370)^2 \tag{51}$$

where ΔH is the terminal height of the ray at 370 km minus the launch height, H_t, and α is the ray launch angle. Then k is defined as

$$k = 1/(Q\ a) \qquad\qquad 1 \leq k \leq 5 \tag{52}$$

where a is the mean earth radius of 6371 km. In a standard atmosphere, $k = 4/3$.

3.1.5 Optical Region Limits

The expression for F in Eq. 5 is valid for all values of Θ so that the path-length difference, δ, is greater than or equal to one-quarter wavelength ($\pi/2$ radians), or the grazing angle is equal to a limit given by Reed and Russell (1966) at which the spherical earth divergence factor becomes invalid. This limit is given by the expression

$$\psi_{lim} = \tan^{-1} [0.001\ \lambda)/(2\ \pi\ a_e)]^{1/3} \simeq (0.01957)/(k\,f\,)^{1/3} \tag{53}$$

where ψ is the grazing angle, λ is the wavelength in meters, a_e is the effective earth radius, and f is the frequency in megahertz.

The optical region maximum range may be reduced from that calculated for the applicable optical region limit above if the surface-based duct height is not zero. If the transmitter is in a surface-based duct, then the end of the optical region must correspond to a direct-ray elevation angle greater than or equal to the critical angle, α_c. If the value of the elevation angle, α, corresponding to the quarter-wavelength or grazing angle limit value of Θ, above, is not greater than α_c, then the optical region limit is taken to be the first optical region peak ($\Theta\ =\ 2\pi$, 4π, etc.) that is associated with a value of α greater than α_c. This range is determined by finding the value of Θ as a function of α_c. $\Theta(\alpha_c)$ can be obtained by using the ray trace equations to find the range corresponding to α_c, that is

$$r\,(\alpha_c) = \{[\alpha_c^{\ 2} + 0.002(H_r\ -\ H_t)/a_e]^{1/2}\ -\ \alpha_c\}a_e \tag{54}$$

where $dMdh_i = 1/a_e$ for the single-gradient atmosphere. Once the range is known, the value of Θ is obtained by determining, in order, the reflection point range, r_1, the effective terminal heights, the path-length difference, δ, the grazing angle, ψ, and the magnitude of phase change caused by reflection, Φ. If $\Theta(\alpha_c)$ is less than, or equal to, 2π (the first optical region peak) and greater than the quarter-wavelength or grazing angle limit, then $\Theta(\alpha_c)$ is the optical region limit. If $\Theta(\alpha_c)$ is greater than 2π, then the next optical region peak with $\Theta = n2\pi > \Theta(\alpha_c)$, n = 2, 3, 4, etc., is taken to be the end of the optical region. (This range is determined by decreasing the range from that of $r(\alpha_c)$ and determining a new value of Θ for each range until the desired range is found.) If both terminal heights are inside the surface-based duct, then the end of the optical region is defined by the quarter-wavelength or grazing angle limit as before.

3.2 DIFFRACTION/INTERMEDIATE REGION MODELS

Beyond the horizon, the chief contributions to the electric field are from diffraction and, at somewhat greater ranges, tropospheric scatter. The diffraction field can be represented as a sum over the possible number of modes which are the solution to the fundamental equation of mode theory. For a standard atmosphere, the series describing the field converges rapidly and only a single mode is necessary to adequately determine the field. A single mode may also describe the field in the presence of evaporation ducts or surface-based ducts caused by elevated layers, especially the former. However, close to the horizon, the series solution converges rather slowly. This is the "intermediate region," and a method of "bold interpolation" originally described by Kerr (1951) is used to estimate the field in this region. This method involves a linear interpolation on the logarithm of the pattern propagation factor from the last valid range in the optical region to the first range in the diffraction region.

The minimum range at which the diffraction field solutions are applicable and the intermediate region ends is given by Reed and Russell (1966) as

$$r_d = r_{hor} + 230.2\,(k^2/f)^{1/3} \qquad \text{(km)} \tag{55}$$

where the horizon range is given by

$$r_{hor} = 3.572\,[(k\,H_t)^{1/2} + (k\,H_r)^{1/2}] \qquad \text{(km)} \tag{56}$$

for H_t and H_r in meters. A minimum effective earth radius of $k = 1.33$ is assumed for the calculation of r_d.

The diffraction/intermediate region models are used to determine propagation loss as a function of height and range for ranges and heights below the lower angular limit of the optical interference region. There are three models used to calculate loss in this region. If the surface-based duct height is zero, then the loss is calculated by using a model derived from the NOSC waveguide program. If a surface-based duct is present, an empirical model is used to calculate loss. At somewhat greater ranges, troposcatter loss is calculated by using a model taken from Yeh (1960). The model has been modified by the addition of a "frequency gain" factor from Rice, et al. (1965) that gives better values for low-altitude paths. The troposcatter loss is calculated for all ranges beyond r_d and added to the surface-based duct or evaporation duct loss until the troposcatter loss is 18 dB less than the applicable loss. Beyond that point, only the troposcatter loss is calculated.

3.2.1 NOSC Evaporation Duct Model

The evaporation duct loss (in decibels) may be written as

$$L = 51.1 + \Gamma - F_{zt} - F_{zr} + 10\log(\rho) + \alpha\rho - L_d \tag{57}$$

The loss term, L_d, is determined by using

$$L_d = 20 \log [f(\mu)] \tag{58}$$

where the antenna pattern factor, $f(\mu)$, gives a measure of how much energy is directed toward the horizon and μ represents the lowest direct ray angle in the optical region. Γ is the excitation factor, F_{zt} and F_{zr} the height-gain functions for the EM system transmitter and radar target/receiver, respectively, ρ the (scaled) range, and α the attenuation rate. The specific values of these quantities are obtained as functions of the duct height. The functions which produce these values are the result of curve-fitting the various quantities to waveguide program solutions. F is obtained by substituting Eq. 57 into Eq. 3.

The waveguide solutions used to develop the evaporation duct model were made at a single frequency, 9.6 GHz. The evaporation duct solutions for other frequencies share a family resemblance: the height of the duct which produces a particular propagation characteristic varies inversely with the frequency. This fact allows the solutions at 9.6 GHz to be scaled to other frequencies. All actual ranges and heights are multiplied by the scale factors

$$R_N = 4.705\ 10^{-2} f^{1/3} \tag{59}$$

and

$$Z_N = 2.214\ 10^{-3} f^{2/3} \tag{60}$$

respectively, to scale the solutions at other frequencies to the 9.6-GHz values. The coefficients ensure that $R_N = Z_N = 1$ when the frequency is set equal to 9600 MHz. When these scale factors are used, the actual evaporation duct, receiver, and transmitter heights are scaled to the 9.6-GHz equivalents, and the range is similarly changed to conform to the 9.6-GHz requirements. For example, the scaled duct height, Δ, is equal to the actual evaporation duct height, δ, times Z_N. Similarly, if r is the actual range and H_t the actual EM system transmitter height, then the scaled range, ρ, is R_N times r and the scaled transmitter height, z_t, is Z_N times H_t.

The height gains expressed as a function of scaled duct height are of two different forms, depending on whether or not the duct height is sufficient to support a well-trapped mode. The height-gain function (in decibels) for scaled duct heights less than 10.25 meters may be written as

$$F(z) = C1\ z^{C2} + C3\ z^{C4} + C5 \qquad z \geq 1.0 \tag{61}$$

where z is the scaled height of either the EM system transmitter or the radar target/receiver. The Ci are constants that are a function of the scaled duct height. For well-trapped modes (i.e., scaled duct heights between 10.25 and 23.3 meters), two functions are necessary to obtain the height-gains in decibels:

$$F(z) = C1 \ln[\sin(C2\ z^{C3})] + C4 \qquad 1.0 \leq z \leq Z_{max} \tag{62}$$

$$F(z) = C5\ z^{C6} + C7 \qquad z > Z_{max} \tag{63}$$

As before, the coefficients, Ci, are determined from the scaled duct height, and z is the scaled height of the EM system transmitter or radar target/receiver. Z_{max} is calculated by using the formula

$$Z_{max} = 4\, e^{-0.31(\Delta - 10.0)} + 6 \tag{64}$$

where Δ is the scaled duct height. The coefficients for scaled duct heights less than 10.25 meters are calculated by using the following formulas:

$$C1 = (-2.2\, e^{-0.244\Delta} + 17)4.72^{-C2} \tag{65}$$

$$C2 = [4.062361\ 10^{4} - (\Delta + 4.4961)^{2}]^{1/2} - 201.0128 \tag{66}$$

$$C3 = (-33.9\, e^{-0.517\Delta} - 3)4.72^{-C4} \tag{67}$$

$$C4 = [1.43012\ 10^{4} - (\Delta + 5.32545)^{2}]^{1/2} - 119.569 \tag{68}$$

$$C5 = 41\, e^{-0.41\Delta} + 61 \tag{69}$$

The coefficients for scaled duct heights between 10.25 and 23.3 meters are calculated by applying the following formulas:

$$C1 = -0.1189\, \Delta + 5.5495 \tag{70}$$

$$C2 = \{1.3291 \sin[0.218(\Delta - 10)^{.77}] + 0.2171 \ln(\Delta)\}4.72^{-C3} \tag{71}$$

$$C3 = 3/2 \tag{72}$$

$$C4 = 87 - [313.29 - (\Delta - 25.3)^{2}]^{1/2} \tag{73}$$

$$C5 = F_{max}/(Z_{max}{}^{-C6}) \tag{74}$$

$$C6 = (Z_{max}/4.72)(S/F_{max}) \tag{75}$$

$$C7 = 49.4e^{-0.1699(\Delta - 10)} + 30 \tag{76}$$

where

$$S = 4.72\ C1\ C2\ C3\,(Z_{max})^{1/2} / \tan[C2\,(Z_{max})^{C3}] \tag{77}$$

and

$$F_{max} = C1 \ln\{\sin[C2\,(Z_{max})^{C3}]\} + C4 - C7 \tag{78}$$

which are necessary to make the two functions, $F(z)$, and their slopes continuous about Z_{max}. Using these coefficients in the equations will produce height-gain curves which increase with height for scaled duct heights below 10.25 meters. The well-trapped modes have an initial increase with height for a limited range of z near the surface, peak, and then decrease with height to some value, thereafter displaying very little variation with height. The minimum scaled height used for calculating the height gains is 1.0 meter, and heights below this are set equal to this value.

Scaled duct heights greater than 23.3 meters have more than one mode which can propagate in the guide. The effect of the multiple modes is to add constructively at some range/height combinations and destructively at others, a condition similar to the optical region interference. Since this variation is not predictable without using a waveguide program, the scaled duct heights greater than 23.3 meters are treated as 23.3 meter ducts. An example of height-gain curves for evaporation ducts is shown in Fig. 3-3.

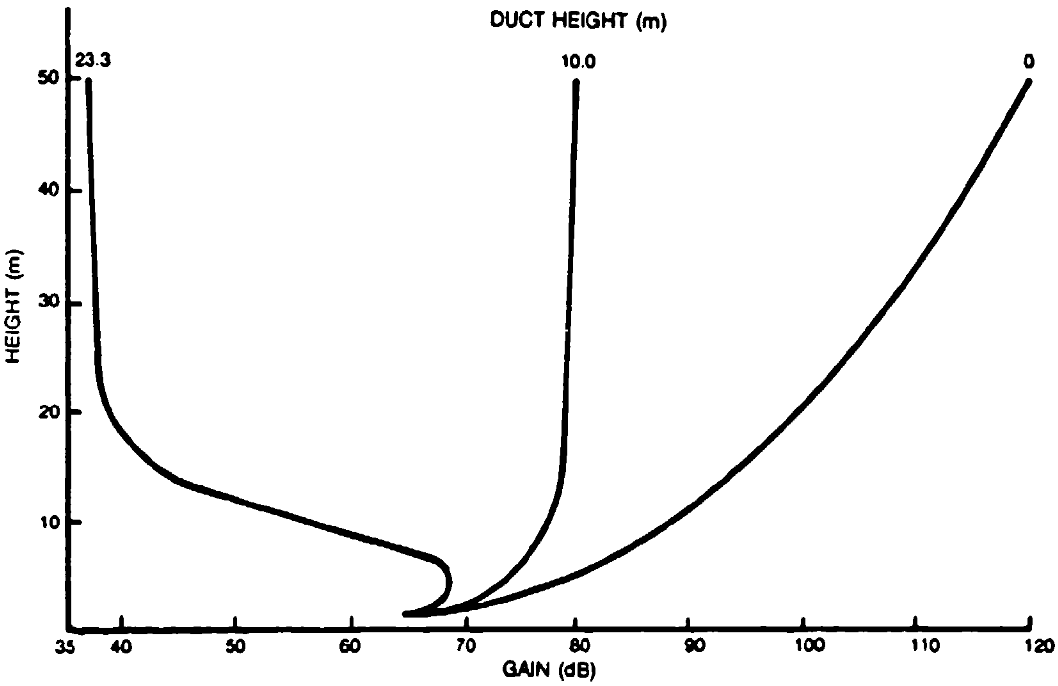

Figure 3-3. Example of 9.6-GHz height-gain curves.

Two factors from Eq. 57 remain to be specified, Γ and α. The excitation factor, which is a measure of the relative strength of the mode, may be obtained, in decibels, by using

$$\Gamma = 216.7 + 1.5526\,\Delta \qquad \Delta \leq 3.8 \qquad (79)$$

$$\Gamma = 222.6 - 1.1771(\Delta - 3.8) \qquad \Delta > 3.8 \qquad (80)$$

The attenuation rate in dB/km is

$$\alpha = \{92.516 - [8608.7593 - (\Delta - 20.2663)^2]^{1/2}\} \qquad (81)$$

for values of $\alpha \geqq 0.0009$, which is the lowest attenuation rate used. It is convenient to replace the attenuation rate term in Eq. 57, $\alpha\rho$, with βr, where r is the actual range and

$$\beta = \alpha\, R_N \qquad (82)$$

The attenuation rates for the higher duct heights may be several orders of magnitude smaller than the standard diffraction (zero-meter duct height) rate.

3.2.2 NOSC Surface-Based Duct Model

The NOSC model for a surface-based duct from elevated layers is not as complex as the evaporation duct model. It is based on an empirical fit of experimental data. The loss (in decibels) may be written

$$L = C - F_{zr} + 20 \log(r) - L_d \tag{83}$$

where F_{zr} is the height-gain function for the receiver/target height and L_d is defined in Eq. 58. Here C (in decibels) is given by $C = 32.44 + 20 \log(f)$. The attenuation rate term is not used in this model, and no range or height scale factors are used either. Similarly, the only height-gain term used in Eq. 83 is the height gain of the radar target/receiver height. As the "guide" dimensions are normally on the order of hundreds of meters, these ducts affect frequencies of 100 MHz and below, unlike the evaporation duct, which only affects frequencies greater than 1 GHz. This model has the disadvantage of being anisotropic with choice of terminal heights. The height-gain term used in the standard propagation model is always calculated for the terminal height, specified as the radar target/receiver height. F is obtained by substituting Eq. 83 into Eq. 3.

The height-gain function for the surface-based duct model is calculated as a function of frequency and duct height for any arbitrary radar target/receiver height, z, as follows:

Case 1: $100 \leq f \leq 150$

$$F_{zr} = -60(z/D - 0.5)^2 \qquad z/D < 0.8 \tag{84}$$

$$F_{zr} = 1.14(z/D)^{-6.26} - 10 \qquad z/D \geq 0.8 \tag{85}$$

Case 2: $150 < f \leq 350$

$$F_{zr} = 10 - 200(z/D - 0.5)^4 \qquad z/D < 1.0 \tag{86}$$

$$F_{zr} = 7.5\,(z/D)^{-13.3} - 10 \qquad z/D \geq 1.0 \tag{87}$$

Case 3: $f > 350$

$$F_{zr} = 10 - 200(z/D - 0.5)^4 \qquad z/D < 1.0 \tag{88}$$

$$F_{zr} = 12.5(z/D)^{-8} - 15 \qquad z/D \geq 1.0 \tag{89}$$

Here D is the duct height. An example of the height-gain curves produced by these formulas is given in Fig. 3-4. The shapes of the height-gain curves are characteristic of well-trapped modes, as should be expected from a surface-based duct.

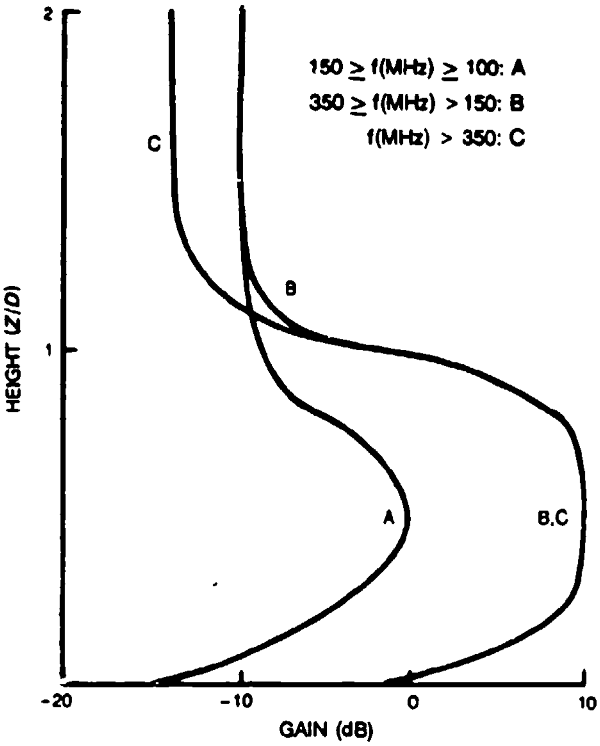

Figure 3-4. Height-gain curve for surface-based duct of arbitrary height.

3.2.3 Troposcatter Region Model

At ranges sufficiently greater than the horizon, scattering from irregularities in the troposphere begins to dominate the electric field. Yeh (1960) gives the troposcatter loss in decibels as

$$L = 114.9 + 0.08984(r - r_{hor})/k + 20 \log (r)$$

$$+ 30 \log (f) - 0.2\, N_s - L_d + H_o \qquad (90)$$

Here r is the range, r_{hor} is the horizon range, N_s is the surface refractivity value, and H_0 is the frequency-gain function from Rice et al. (1965). L_d is defined in Eq. 58. F is obtained by substituting Eq. 90 into Eq. 3.

The frequency-gain function, H_0, is primarily of importance for low antenna heights, especially if the system frequency is very low. The procedure for obtaining H_0 requires a calculation of the effective scattering height, h_0, which is equal to

$$h_o = (s\, r\, \Theta)/(1 + s)^2 \qquad \text{(km)} \qquad (91)$$

where r is the ground range, Θ is the scattering angle, as shown in Fig. 3-5, and s is defined by

$$s = \zeta / \chi \qquad 10.0 \geq s \geq 0.10 \qquad (92)$$

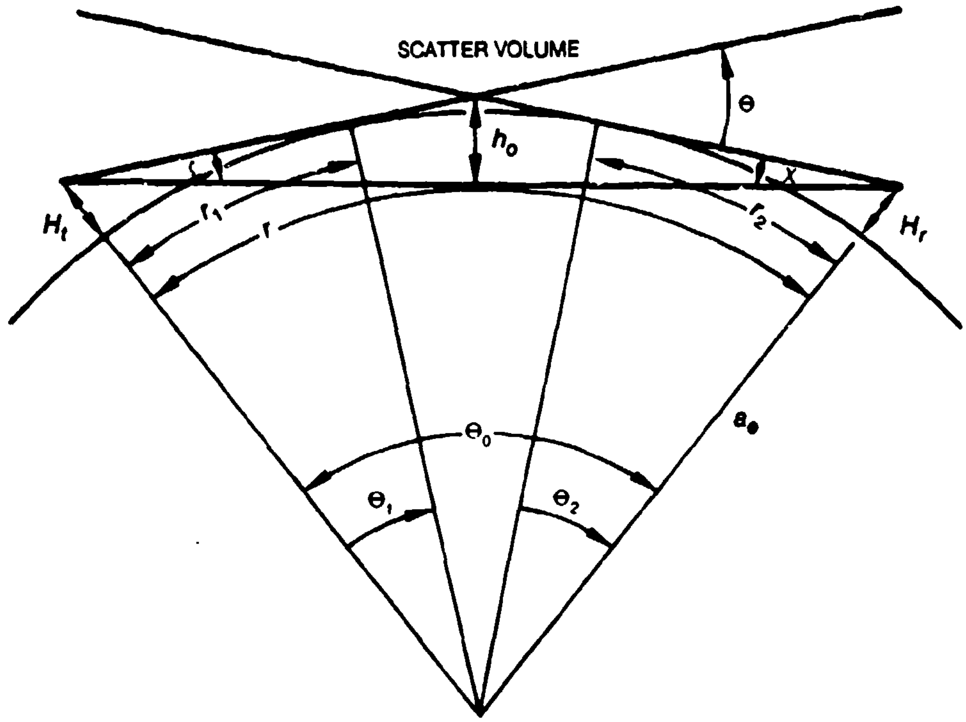

Figure 3-5. Geometry for troposcatter loss calculations.

The angles from these equations are given by

$$\Theta = \Theta_0 + \Theta_1 + \Theta_2 \tag{93}$$

$$\Theta_0 = r/a_e \tag{94}$$

$$\Theta_1 = r_1/a_e \tag{95}$$

$$\Theta_2 = r_2/a_e \tag{96}$$

$$\zeta = \Theta/2 + \Theta_1 + (H_t - H_r)/r \tag{97}$$

$$\chi = \Theta/2 + \Theta_2 + (H_r - H_t)/r \tag{98}$$

in terms of the effective earth radius, a_e, the tangent ray ranges, r_1 and r_2, the terminal heights, H_t and H_r, and the total range, r, as shown in Fig. 3-5. The tangent ranges, r_1 and r_2, are equal to

$$r_1 = (0.002\, a_e\, H_t)^{1/2} \quad \text{(km)} \tag{99}$$

$$r_2 = (0.002\, a_e\, H_r)^{1/2} \quad \text{(km)} \tag{100}$$

The frequency-gain function is then defined as

$$H_o = H_1 + \Delta H_o \qquad H_o \geq 0.0 \quad \text{(dB)} \tag{101}$$

where

$$H_1 = [H_0(R_1) + H_0(R_2)]/2 \tag{102}$$

If ΔH_0 is greater than H_1, then H_0 is equal to twice the value of H_1. The function H_1 is calculated by using

$$H_0(R_1) = c_1 (R_1 + c_2)^{-4/3} \tag{103}$$

$$H_0(R_2) = c_1 (R_2 + c_2)^{-4/3} \tag{104}$$

where R_1 and R_2 are functions of the terminal heights and EM system frequency, f, in megahertz. These variables are calculated as follows:

$$R_1 = 0.0419 f H_t \Theta \tag{105}$$

$$R_2 = 0.0419 f H_r \Theta \tag{106}$$

And the terms c_1 and c_2 are defined as

$$c_1 = 16.3 + 13.3 \eta_s \tag{107}$$

$$c_2 = 0.40 + 0.16 \eta_s \tag{108}$$

The factor η_s must be calculated as a function of h_0 in the following manner:

$$\eta_s = 0.5696 h_0[1 + (0.031 - 0.00232 N_s + 5.67 N_s^2 10^{-6})\exp(-3.8 h_0^6 10^{-6})]$$

$$5.0 \geq \eta_s \geq 0.01 \tag{109}$$

The remaining term, ΔH_0, is calculated by using

$$\Delta H_0 = 6 [0.60 - \log(\eta_s)] \log(s) \log(q) \quad \text{(dB)} \tag{110}$$

where q is given by

$$q = R_2/(s R_1) \qquad 10.0 \geq q \geq 0.10 \tag{111}$$

The correction term ΔH_0 is zero for $\eta_s = 4.0$, $s = 1.0$, or $q = 1.0$ and has a maximum value of 3.6 dB for highly asymmetrical paths when $\eta_s = 1.0$.

3.3 STANDARD PROPAGATION MODEL FORTRAN PROGRAM

The standard propagation model is implemented in a program called FFACTR. FFACTR is written in ANSI Fortran 77 with the allowable MIL-STD-1753 extensions. FFACTR will return a single value for the propagation factor in decibels for the specified EM system and environmental parameters of Table 2-1 and Table 2-2. To use FFACTR, the operator must compile and link the routines that comprise the program. A complete list of all subroutines is included in the appendix. The subroutines are listed in alphabetical order following lists of the MAIN and FFACTR routines and the common block "include" files. No EM system or environmental libraries are supplied with FFACTR, though a limited number of environmental and EM system data files are supplied for test purposes.

Because the standard propagation model is designed to return a single value for a collection of input data, FFACTR behaves more like a subroutine than a stand-alone program. A demonstration program, MAIN, which acts as a driver for the FFACTR program, is included to demonstrate one possible use of the program. The driver simulates an inbound radar target by supplying FFACTR with constant environmental and, except for the range, EM system parameters. The range decreases from 100 km to 10 km in 10-km increments. In addition to MAIN, several subroutines are provided which allow the operator to enter environmental and EM system data from the keyboard or files. These subroutines, SYSFIL, ENVFIL, ENVINP, and SYSINP, are not intended as part of the FFACTR program, but only for use in verifying the correct operation of the FFACTR program. The operational sequence of FFACTR is detailed in the following paragraphs.

First, the environmental and EM system data are entered and the FFACTR subroutine is called. FFACTR then calls the MPROF subroutine to process the M-unit, (M_i), and height, (H_i), array data and to construct the $dMdh_i$ array. The profile is inspected for surface-based ducts by the DUCTS subroutine and, if one exists that contains the EM system transmitter height, the critical angle, α_c, is calculated. Subroutines PUSH and INSRT are used by MPROF to insert an M-unit array value at the transmitter height. Upon return from the MPROF subroutine, the GETK subroutine is called to perform the raytrace that is used to obtain the effective earth radius factor. Next, several subroutines are called to initialize various constants required by the program. ANTPAR converts the EM system antenna parameters from degrees to radians and establishes the angular limits for the antenna patterns. OPCNST is used to initialize various constants used in the optical region processing, and DCONST performs the same task for the diffraction/troposcatter region calculations.

Once the initialization phase is completed, the next step is to determine if the input range is in the optical, intermediate, or diffraction region. Subroutine OPLIMIT is used to calculate the optical region maximum range and the value of L_d which is used to determine F in the diffraction and intermediate regions. OPLIMIT makes use of the ANTPAT, OPFFAC, R1ITER, REF, and RUFF subroutines. OPFFAC is used to calculate most of the terms used in antenna pattern factors, $f(\epsilon_i)$. REF returns R and Φ, and RUFF returns the surface roughness coefficient. R1ITER is used to determine the reflection point range. If the input range is less than the optical region limiting range, subroutine OPTICF is called to determine the exact value of the pattern propagation factor, F, to be returned. This requires a solution to the cubic equation (Eq. 9) to determine the reflection point range. OPTICF uses a Newton iteration technique to determine the reflection point range and then utilizes OPFFAC, ANTPAT, REF, and RUFF to return the value of the pattern propagation factor, F.

If the input range is greater than the optical region maximum range, it is compared to r_d, the minimum range where the diffraction region calculations are valid. If the range value is greater than r_d, then the DIFF subroutine is used to determine the value of F for this region. DIFF obtains the appropriate F value by calling the HGAIN and TROPO subroutines. HGAIN returns the value of the height-gain function for both evaporation and surface-based ducts from elevated layers and TROPO returns F for the troposcatter region. DIFF calculates the value of F for either a surface-based duct or an evaporation duct. If a surface-based duct containing the transmitter exists, it is assumed to be the dominant propagation mechanism and F is calculated by using Eq. 83 and Eq. 3. If no surface-based duct exists, then F is determined by using Eq. 57 and Eq. 3. The diffraction region F is then compared to the troposcatter region F. If the troposcatter F value is within 18 dB, the fields are added and the resulting F is returned. If the troposcatter F is 18 dB less than the diffraction F value, then troposcatter is the dominant propagation mechanism and the troposcatter F is returned.

If the input range is less than r_d and greater than the optical region maximum range, then the range is in the intermediate region and a linear interpolation of the propagation factor in decibels versus range is performed to obtain F. This is accomplished by calling the DIFF subroutine to obtain the value of F at r_d. Then, a linear interpolation between the value of F at the optical region maximum range, obtained from OPLIMIT, and F at r_d is performed to obtain the value of F at the specified range.

FFACTR is structured to return a single value of F for a given set of inputs. This structure is the most efficient one if the input data are going to vary for each case in some arbitrary fashion. This is not the case, for example, in the demonstration program, MAIN, where only the range varies. Since the environment and the rest of the EM system parameters remain constant for each call to FFACTR, there is a fair amount of redundancy in the calculation of the antenna pattern constants, the effective earth radius, and the optical and diffraction region constants. If FFACTR is always going to be used in such a fashion, it would be best to remove these calculations from FFACTR and place them in the calling routine. For example, if the environmental parameters are constant and the EM system height, H_t, is a constant, then the effective earth radius is also a constant. In this case, the DUCTS, GETK, INSRT, MPROF, and PUSH subroutines should be placed in the calling routine. If the EM system is fixed, then the antenna constants subroutine, ANTPAR, should be in the calling routine. If the environment is a constant and the only independent EM system variable is range, as in the MAIN routine supplied, then the DCONST, OPCNST, and OPLIMIT subroutines should also be placed in the calling routine. This would mean that ANTPAR, DCONST, DUCTS, GETK, INSRT, MPROF, OPCNST, and PUSH subroutines would only be called once for each environment and geometry instead of the multiple calls that occur for each range as the FFACTR routine is presently structured. If the environment is to remain constant, but both the radar target/receiver height and the range can vary in an arbitrary fashion, then the DCONST, OPCNST, and OPLIMIT subroutines would have to remain in FFACTR, but the others could be removed to the calling routine.

4.0 TEST CASES

A number of EM system and environmental inputs are required to determine the propagation factor. Table 4-1 lists EM system parameters for five test case systems, Sys1 through Sys5, which are used to verify the proper operation of the FFACTR program. The input parameters that are listed correspond to the variable names of Section 3.0, except for the polarization and antenna type entries. Range is not listed as an EM system input in Table 4-1, since the demonstration program, MAIN, supplies a constantly decreasing range that varies from 100 km to 10 km in 10-km increments for each EM system and environmental data set selected. Three different environmental test case conditions, Env1 through Env3, are listed in Table 4-2. The environment of Env1 corresponds to a standard atmosphere M-unit profile, a 0-meter evaporation duct height, and 10 knots of wind. Env2 uses the same M-unit profile as Env1, but the wind speed is 0 knots, and a 10-meter evaporation duct is present. Env3 has an M-unit profile that contains a 100-meter surface-based duct, 0-meter evaporation duct, and 5 knots of wind. The environmental data sets also list the parameters using the variable names of Section 3.0. Each of the EM system test cases uses each of the environments.

Table 4-1. EM system test set input data.

Parameter	Sys1	Sys2	Sys3	Sys4	Sys5
f, MHz	100.0	300.0	5000.0	9600.0	15,000.0
H_t, m	20.0	30.0	20.0	1.0	50.0
H_r, m	30000.0	2000.0	20.0	20.0	120.0
Polarization[a]	H	V	C	H	H
Antenna Type[b]	S	C	H	S	O
BW, deg	10.0	10.0	2.0	2.0	n/a
μ_o, deg	0.0	1.0	0.0	1.0	n/a

[a]H = horizontal
V = vertical
C = circular

[b]S = $\sin(x)/x$
C = $\csc^2$
H = generic height-finder
O = omnidirectional

Table 4-2. Environmental test set input data.

Parameter	Env1	Env2	Env3
δ, m	0.0	10.0	0.0
W_s, kt	10.0	0.0	5.0
H_1, M_1, (m, M)	(0.0, 339.0)	(0.0, 339.0)	(0.0, 350.0)
H_2, M_2, (m, M)	(1000.0, 457.0)	(1000.0, 457.0)	(270.0, 381.9)
H_3, M_3, (m, M)	(10000.0,1519.0)	(10000.0,1519.0)	(300.0, 340.0)
H_4, M_4, (m, M)	n/a	n/a	(1000.0, 422.6)
H_5, M_5, (m, M)	n/a	n/a	(10000.0,1484.6)

Tables 4-3 through 4-5 list the expected output data for the different environmental test cases. The outputs, in decibels, are listed to the nearest 0.1 dB, and the FFACTR program is considered to be operating correctly if the output is within 0.1 dB of the value listed in the appropriate table.

Table 4-3 Output data for environment 1.

Range (km)	F(dB)				
	Sys1	Sys2	Sys3	Sys4	Sys5
100.0	-37.2	-0.6	-56.1	-62.5	-58.0
90.0	-25.2	-5.7	-55.5	-61.8	-50.2
80.0	-39.4	-1.6	-54.9	-61.2	-28.1
70.0	-25.8	2.4	-54.1	-60.5	-4.7
60.0	-25.3	1.4	-49.9	-59.8	0.8
50.0	-44.6	-2.1	-37.1	-59.0	2.7
40.0	-47.4	1.0	-23.1	-53.7	2.7
30.0	-26.2	1.0	-9.1	-38.2	0.3
20.0	-49.8	1.0	3.5	-22.6	-11.7
10.0	-43.2	-0.1	-1.6	-7.7	-4.0

Table 4-4. Output data for environment 2.

Range (km)	F(dB)				
	Sys1	Sys2	Sys3	Sys4	Sys5
100.0	-37.1	-0.6	-39.3	-25.5	-11.3
90.0	-25.1	-5.7	-33.7	-22.9	-11.8
80.0	-39.3	-1.6	-28.1	-20.4	-8.1
70.0	-25.7	2.5	-22.5	-18.0	-1.1
60.0	-25.1	1.4	-17.0	-15.6	0.8
50.0	-44.6	-2.1	-11.9	-13.4	2.7
40.0	-47.9	1.0	-7.3	-11.3	2.8
30.0	-25.9	1.0	-2.8	-11.1	0.6
20.0	-61.7	1.0	3.5	-12.2	-18.9
10.0	-44.3	-0.1	-1.6	-7.7	-24.7

Table 4-5. Output data for environment 3.

Range (km)	F(dB)				
	Sys1	Sys2	Sys3	Sys4	Sys5
100.0	-41.7	-5.1	2.9	0.1	5.6
90.0	-24.8	-4.0	2.9	0.1	1.8
80.0	-44.1	-0.9	2.9	0.1	1.5
70.0	-26.0	2.8	2.9	0.1	-4.9
60.0	-25.4	0.2	2.1	0.1	0.5
50.0	-50.5	-1.2	1.3	0.1	5.0
40.0	-55.4	0.5	0.5	-3.2	4.6
30.0	-25.7	0.8	-0.3	-7.9	5.3
20.0	-54.0	0.9	5.1	-12.7	5.6
10.0	-43.6	-0.1	1.6	-6.6	0.6

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Appendix

STANDARD PROPAGATION MODEL PROGRAM LISTING

```
c
c **************************** MAIN PROGRAM **************************
c
c INPUTS:       VARIABLE    VARIABLE DESCRIPTION    (VALID RANGE, UNITS)
c
c EM SYSTEM:    freq        SYSTEM FREQUENCY           (100 - 20000 MHz)
c               ht          TRANSMITTER ANTENNA HEIGHT     (1 - 100 m)
c               hr          RECEIVER/TARGET HEIGHT       (1 - 30000 m)
c               polar       ANTENNA POLARIZATION    (HORIZONTAL = "H",
c                                      VERTICAL = "V", CIRCULAR = "C")
c               antype      ANTENNA TYPE       (OMNIDIRECTIONAL = "O",
c                              SIN(X)/X = "S", COSECANT-SQUARED = "C",
c                                             GENERIC HT-FINDER = "H")
c               bwidth      ANTENNA BEAM WIDTH              (.5 - 45 DEG)
c               elevat      ANTENNA ELEVATION ANGLE      (-10 - +10 DEG)
c                             (0 DEGREES IS HORIZONTAL, NORMAL POINTING
c                              ANGLE FOR SHIPBOARD RADAR SYSTEMS)
c               r           RANGE AT WHICH F-FACTOR IS DESIRED (1-1000km)
c
c ENVIRONMENTAL:
c               delta       EVAPORATION DUCT HEIGHT          (0 - 40 m)
c               height(i)   HEIGHT ARRAY IN METERS - UP TO 30 ELEMENTS
c               munits(i)   M-UNIT ARRAY CORRESPONDING TO HEIGHT ARRAY
c               wind        WIND SPEED                    (0 - 50 KNOTS)
c
c PROGRAM OUTPUT:
c               ff          20*LOG10( PATTERN PROPAGATION FACTOR )  dB
c                           [ff values that are positive indicate a
c                           signal level above the free-space field
c                           at that range. Negative values indicate
c                           signal levels below the free-space field.]
c
c   The following program is a demonstration driver for the FFACTR
c   (sub)routine.  This program is included to show possible uses for
c   the FFACTR program.  The FFACTR program returns a value (in dB)
c   of 20*LOG(F) where F is the pattern propagation factor.  F is
c   defined as the ratio of the actual field at some point, to
c   the free-space field at that same point.  (The free-space field
c   is determined for an isotropic antenna.)  Because FFACTR can be
c   called in any arbitrary fashion it is not necessarily the most
c   efficient structure for producing a product such as a loss-versus-
c   range plot.  If only the range is to be varied, with constant
c   terminal heights, then the ANTPAR, DCONST, DUCTS, GETK, INSRT,
c   MPROF, OPCNST and PUSH subroutines should be moved to the calling
c   routine so they aren't called for every new range point.
c
c                            START DEMO PROGRAM
c
      include 'envsys.common'
c
c
      real*4  ff, r, rloss
      integer*2 ZW
c
c       Enter the environmental parameters.
c
      call envinp(delta, height, Munits, wind, nmax)
c
c       Enter the EM system parameters.
```

```
c
      call sysinp(freq,ht,hr,polar,antype,bwidth,elevat)
c
      fsterm = 32.45 + 20.0 * ALOG10(freq)
      dr = 10.0
      r = 100.0 + dr
c
c       Call FFACTR for the EM system and environmental parameters
c       entered above.  Calculate the propagation factor for several
c       ranges in the loop below.  Print the output values of prop-
c       agation factor and propagation loss for each range.
c
      ZW = 6
      DO i = 1, 10
        r = r - dr
        call ffactr(r, FF)
        rloss = fsterm + 20.0 * ALOG10(r) - ff
        write(ZW,1000) r,rloss,ff
 1000 Format('Range = ',f5.1,' km.  Loss = ',f6.2,' dB',' F = ',
     1        f6.1,' dB')
      END DO
c
c                            END DEMO PROGRAM
c
      END
```

```
c
c   Subroutine ffactr
c
c   FFACTR returns the value of the pattern propagation factor, F, in dB
c   for specified range , EM system parameters and environmental para-
c   meters.
c
c   Variables:        Description:
c
c     alphac       Critical angle - 1st angle not trapped in surface-
c                    based duct.
c     antbwr       Antenna vertical beamwidth in radians.
c     antelr       Antenna elevation angle in radians.
c     antfac       Antenna pattern constant.
c     antype       Antenna type: O - omnidirectional, S - sin(x)/x,
c                    C - cosecant-squared, H - height-finder.
c     bwidth       Antenna vertical beam width in degrees.
c     delta        Evaporation duct height in meters.
c     deltaf       Variable used in linear interpolation of F in the
c                    intermediate region.
c     dffac        Diffraction field constant, dB.
c     difac        Diffraction field constant, dB.
c     elevat       Antenna elevation angle in degrees.
c     elmaxr       Maximum elevation angle in main beam of antenna, rad.
c     ff           Pattern propagation factor, F, in dB.
c     freq         EM system operating frequency in MHz.
c     frsubd       Pattern propagation factor at rsubd.
c     fzr          Evaporation duct height-gain at hr, dB.
c     fzt          Evaporation duct height-gain at ht, dB.
c     height       Array containing environmental input height values
c                    corresponding to the Munit array.
c     hdif         Height difference between receiver/target and
c                  transmitter heights in km.
c     ht           Transmitter height in m.
c     hr           Receiver/target height in m.
c     h1           Lower height of hr, ht, in m
c     h2           Higher height of hr, hr, in m.
c     lvlant       Transmitter height level in hmrs and dMdh arrays.
c     Munits       Array containing environmental input M-unit values.
c     nmax         Integer number of layers in Munits and height arrays.
c     opmaxd       Maximum range in the optical interference region, km.
c     opmaxf       F at opmaxd.
c     patrfac      Antenna pattern constant.
c     pd           Path-difference between direct and sea-reflected rays.
c     polar        Antenna polarization: H - horizontal, V - vertical,
c                    C - circular.
c     psi          Grazing angle in radians.
c     r            Range in km.
c     rsdfac       Constant used to calculate rsubd.
c     rsubd        Minimum range where diffraction field solutions are
c                    applicable, km.
c     sbdht        Surface-based duct height, m.
c     theta        Total phase difference between direct and sea-
c                    reflected rays including phase lag due to reflection.
c     wind         Wind speed in kts.
c

      SUBROUTINE ffactr(r, FF)
c
c
      real*4  deltaf, ff, fzr, fzt, opmaxd, opmaxf, frsubd, r
      real*4  dMdh(32), hmrs(32)
      integer*2 lvlant, ntot
c
```

```
      include 'ffac.common'
      include 'envsys.common'
c
c       Call mprof to insert a profile level at Ht and determine if
c       any surface-based ducts are present.  If a surface-based duct
c       is present calculate critical angle, alphac.
c
      call mprof(height, Munits, ht, NMAX, ALPHAC, DMDH, HMRS,
     1           SBDHT, NTOT)
c
c       Call getk to determine the effective earth radius factor, rk.
c
      call getk(alphac, dMdh, hmrs, ntot, ht, RK)
c
c       Define h1, h2 for opticf subroutine.  These are swapped for
c       ht>hr because the iteration loop for r1 in opticf works most
c       efficiently when the lowest height is the transmitter height.
c
      IF (ht .GT. hr) THEN
        h1 = hr
        h2 = ht
      ELSE
        h1 = ht
        h2 = hr
      END IF
c       Define optical region constants.
      call opcnst
      hdif = (hr - ht) * 1.0e-3
c       Initialize antenna parameters.
      call antpar(antype,bwidth,elevat,ANTBWR,ANTELR,ANTFAC,
     1                                  ELMAXR,PATRFAC)
c       Define diffraction/troposcatter region constants.
      call dconst
      call hgain(hr, FZR)
      IF (sbdht .EQ. 0.0) THEN
        call hgain(ht, FZT)
        dffac = dffac - fzt
      END IF
      difac = dffac - fzr
      rsubd = 3.572 * (SQRT(rkmin * ht) + SQRT(rkmin * hr)) + rsdfac
c       Determine maximum range and f-factor in optical region.
      call oplimit(OPMAXD,OPMAXF)
      IF (r .GE. rsubd) THEN
c           Calculate loss for range in diffraction/troposcatter region.
        call diff(r, FF)
      ELSE
        IF  (r .GT. opmaxd) THEN
c             Range is in intermediate region - use linear interpolation
c             on log of the f-factor.
          call diff(rsubd,FRSUBD)
          deltaf = (r - opmaxd) * (opmaxf - frsubd) / (opmaxd-rsubd)
          ff = opmaxf + deltaf
        ELSE
c             Range is in the optical interference region.
          IF (r .LE. opmaxd) call opticf(polar,r,PD,PSI,THETA,FF)
        END IF
      END IF
      ff = - ff
      RETURN
      END
```

```
c
c     'envsys.common' include file
c
c     EM system parameter common blocks
c
      common  / emsystem  / freq, hr, ht
      common  / emsystem  / polar, antype, bwidth, elevat
c
c     Environmental parameter common blocks
c
      common  / enviro    / delta, height, Munits, nmax, wind
c
c
      real*4 delta, height(30), Munits(30), wind
      real*4 freq, ht, hr, bwidth, elevat
      character*1 antype, polar
      integer*2 nmax
c
```

```
c
c     'ffac.common' include file
c
      common  / comffactr / ae, ae2, aeth, alpha, alphac, antbwr
      common  / comffactr / antelr, antfac, atten
      common  / comffactr / c1, c2 ,c3 ,c4 ,c5, c6, c7
      common  / comffactr / del, dffac, difac, elmaxr, exloss
      common  / comffactr / fsterm, hbar, hbfreq, hdif, hmin, h1
      common  / comffactr / h2, horznl, patd, patrfac, rk, rkmin
      common  / comffactr / rnimag, rnreal, rsdfac, rsubd, sbdht
      common  / comffactr / thefac, twoae, zfac, zmax

      real*4 ae, ae2  aeth, alpha, alphac, antbwr, antelr, antfac,
     1        atten, c1, c2, c3, c4, c5, c6, c7, del, dffac, difac,
     2        elmaxr, exloss, fsterm, hbar, hbfreq, hdif, hmin,
     3        horznl, h1, h2, patd, patrfac, rk, rkmin, rnimag,
     4        rnreal, rsdfac, rsubd, sbdht, thefac, twoae, zfac, zmax
c
```

```
c
c  Subroutine antpar
c
c  ANTPAR is used to intitialize antenna parameters for use in
c  calculating antenna pattern factors.
c
c  Variable:        Description:
c
c    Antbwr      Antenna beam width in radians.
c    Antelr      Antenna elevation angle in radians.
c    Antfac      Antenna pattern constant.
c    Antype      Antenna type:  O - omnidirectional
c                               S - Sin(x)/x
c                               C - Cosecant-squared
c                             H - generic Height-finder
c    Bwidth      Antenna beam width, degrees.
c    Elevat      Antenna elevation angle, degrees.
c    Elmaxr      Maximum angle in main beam of antenna, radians.
c    Patrfac     Pattern factor constant for Sin(x)/x antennas,
c                  used to calculate Elmaxr for Sin(x)/x antennas.
c
      SUBROUTINE antpar(antype,bwidth,elevat,ANTBWR,ANTELR,ANTFAC,
     1                  ELMAXR,PATRFAC)
c
c
      real*4 antbwr, antelr, antfac, amax, bwidth, elmaxr,
     1       elevat, pi, patfac, patrfac
      character*1 antype
c
      PI = 3.14159
c      Convert beam width and elevation angle to radians.
      antbwr = 1.745e-2*bwidth
      antelr = 1.745e-2*elevat
      elmaxr = 1.047
      IF (antype .NE. "O") THEN
        IF (antype .EQ. "C") THEN
c           Cosecant-squared antenna pattern constants.
          elmaxr = antelr + .78525
          antfac = SIN(antbwr)
        ELSE
          IF ((antype .EQ. "S").OR.(antype .EQ. "H"))THEN
c              Sin(x)/x and height-finder antenna pattern constants.
            antfac = 1.39157/SIN(antbwr/2.0)
            amax = PI/antfac
            patrfac = -ATAN(amax/SQRT(1.0 - amax*amax))
            IF (antype .EQ. "S") elmaxr = antelr - patrfac
          END IF
        END IF
      END IF
      RETURN
      END
```

```
c
c  Subroutine antpat
c
c  ANTPAT returns the antenna pattern factor for a given angle
c  and antenna type.
c
c  Variable:      Description:
c    alpha        Direct r-y launch angle, radians.
c    antbwr       Antenna beam width in radians.
c    antelr       Antenna elevation angle in radians.
c    antfac       Pattern constant.
c    angle        The angle for which the pattern factor is desired.
c    antype       Antenna pattern type: O - omnidirectional
c                                       S - sin(x)/x
c                                       C - cosecant-squared
c                                       H - generic height-finder
c    patfac       The antenna pattern factor for the given angle.
c    patrfac      Pattern constant.
c
c
      SUBROUTINE antpat(antype,alpha,antbwr,antelr,antfac,patrfac,
     1                  angle,PATFAC)
c
c
      real*4 alpha, alpha0, antbwr, antelr, antfac, angle, apat,
     1       patfac, patrfac, ufac
      character*1 antype
c
      patfac = 1.0
      IF (antype .NE. "O") THEN
c           Antenna types other than omni require calculation.
        IF ((antype .EQ. "H").AND.(alpha .GT. antelr)) THEN
          alpha0 = alpha
        ELSE
          alpha0 = antelr
        END IF
        apat = angle - alpha0
        IF (antype .EQ. "C") THEN
c               Cosecant-squared antenna type.
          patfac = AMIN1(1.0, AMAX1(0.03, 1.0 + apat/antbwr))
          IF (apat.GT.antbwr) patfac = SIN(antbwr)/SIN(ABS(apat))
        ELSE
c               SIN(X)/X antenna type.
          IF (apat .NE. 0.0) THEN
            IF ((angle .LE. alpha0 + patrfac) .OR.
     1          (angle .GE. alpha0 - patrfac)) THEN
c             Antenna pattern is limited to main lobe only.
              patfac = 0.03
            ELSE
c               Sin(x)/x calculation.
                ufac = antfac*SIN(apat)
                patfac = AMIN1(1.0, AMAX1(0.03, SIN(ufac)/ufac))
              END IF
          END IF
        END IF
      END IF
      RETURN
      END
```

```
c
c  Subroutine dconst
c
c  DCONST initializes variables for the diffraction and troposcatter
c  region routines.
c
c  Variable:      Description:
c    arg          Evaporation duct model temporary variable.
c    atten        Diffraction region attenuation rate in dB/km.
c    c1 - c7      Evaporation duct constants for height-gain function.
c    del          Scaled evaporation duct height (delta * zfac).
c    delta        Evaporation duct height, m.
c    dffac        Diffraction field constant in dB.
c    fmax         Evaporation duct model temporary variable.
c    freq         EM system frequency in MHz.
c    fsterm       Free-space loss term, dB.
c    gamma        Evaporation duct excitation factor in dB.
c    hmin         Minimum allowable height, m.
c    rfac         Evaporation duct range scale factor.
c    rk           Effective earth radius factor.
c    rkmin        Minimum rk used for calculation of the diffraction
c                 region minimum range, rsubd.
c    rsdfac       Constant used for rsubd calculation.
c    sbdht        Surface-based duct height, m.
c    zfac         Evaporation duct height scale factor.
c    zmax         Evaporation duct height variable.  Height where the
c                   two different equations for the height-gain factors
c                   must be equal (del >= 10.25 meters).
c
      SUBROUTINE dconst
c
c
      real*4 arg, fmax, gamma, rfac, slope
c
      include 'ffac.common'
      include 'envsys.common'
c
c
c       Diffraction region constants.
c
      IF (sbdht .GT. 0.0) THEN
c
c         Surface-based duct model.
c
        del = 0.0
        hmin = 1.0
        atten = 0.0
        dffac = fsterm
c
      ELSE
c
c         The following terms are for NOSC evap duct model.
c
        rfac = 0.04705 * freq**(1./3.)
        zfac = 0.002214 * freq**(2./3.)
        hmin = 1.0
        del = AMIN1(delta * zfac, 23.3)
c
c           Constants for scaled evap. duct heights >= 10.25 meters.
c
          c1 = -0.1189 * del + 5.5495
          c3 = 3./2.
          c2 = 1.3291 * SIN(0.218 * (del-10.0)**0.77) + 0.2171*ALOG(del)
          c2 = c2 * 4.72**(-c3)
```

```
          c4 = 87.0 - SQRT(313.29 - (del - 25.3)**2)
          zmax = 4.0 * EXP(-0.31*(del - 10.0)) + 6.0
          arg = c2 * zmax**c3
          slope = 4.72 * c1 * c2 * c3 * SQRT(zmax) / TAN(arg)
          c7 = 49.4 * EXP(-0.1699*(del - 10.0)) + 30.0
          fmax = c1 * ALOG(SIN(arg)) + c4 - c7
          c6 = (zmax/4.72) * slope / fmax
          c5 = fmax / zmax**c6
        ELSE
c
c           Constants for scaled evap. duct heights <= 10.25 meters.
c
          c2 = SQRT(40623.61 - (del + 4.4961)**2) - 201.0128
          c1 = (-2.2 * EXP(-0.244*del) + 17.0)*4.72**(-c2)
          c4 = SQRT(14301.2 - (del + 5.32545)**2) - 119.569
          c3 = (-33.9 * EXP(-0.5170001*del) - 3.0)*4.72**(-c4)
          c5 = 41.0 * EXP(-0.41*del) + 61.0
        END IF
        atten = 92.516 - SQRT(8608.7593 - (del - 20.2663)**2)
        IF (atten .LT. 0.0009) atten = 0.0009
        atten = atten * rfac
        IF (del .LE. 3.8) gamma = 216.7 + del * 1.5526
        IF (del .GT. 3.8) gamma = 222.6 - (del - 3.8) * 1.1771
        dffac = 51.1 + gamma + 10.0 * ALOG10(rfac)
      END IF
c
c        Constants used to calculate rsubd, the minimum
c        range at which the diffraction field solutions are valid.
c
      rkmin = AMAX1(rk, 1.3333)
      rsdfac = 230.2 * (rkmin**2 / freq)**(1.0/3.0)
c
      RETURN
      END
```

```
c
c   Subroutine diff
c
c   Subroutine DIFF returns the diffraction field propagation factor
c   as a function of range.
c
c   VARIABLES:       DESCRIPTION:
c     atten        NOSC model attenuation rate in dB/km
c     delta        Evaporation duct height in meters
c     dfloss       - 20*LOG(F), where F is the propagation factor
c     dloss        Diffraction field strength in dB
c     dif          Temporary variable
c     difac        NOSC evaporation duct model constant
c     diffe        NOSC evaportion duct model loss in dB
c     exloss       Antenna loss for lowest angle in optical region (dB)
c     r            range in km
c     tloss        Troposcatter loss from Tropo Subroutine in dB
c
c
      SUBROUTINE diff(r, DFLOSS)
c
c
```

```
      real*4   dif, dfloss, dloss, diffe, r, tloss, tlr
c
      include 'ffac.common'
      include 'envsys.common'
c
      tlr = 10.0*ALOG10(r)
      IF (sbdht .EQ. 0.0) THEN
c            Calculate the evaporation duct loss.
        dloss = difac + tlr + atten*r
      ELSE
c            Calculate the surface based duct loss.
        dloss = difac + 2.0*tlr
      END IF
      dloss = dloss + exloss
c
c       Calculate troposcatter loss and compare to dloss.  If the
c       difference is +/- 18 dB add the two fields togather.
c
      call tropo(r,tloss)
      dif = dloss - tloss
      IF (dif .GE. 18.0) THEN
c         Troposcatter field dominates.
         dloss = tloss
      ELSEIF (dif .GE. -18.0) THEN
c         Add troposcatter and diffractions fields togather.
         dloss = dloss - 10.0*ALOG10(1.0 + 10.0**(dif/10.0))
      END IF
c
c      -20*LOG(F) = actual loss - free space loss
c
      dfloss = dloss - fsterm - 2.0*tlr
      RETURN
      END
```

```
c
c  Subroutine ducts
c
c  DUCTS builds an array containing the top, bottom, and
c  minimum refractivity of all the major ducts in the
c  atmosphere refractivity profile.
c
c  Variable:        Description:
c    dct          3,*  duct parameters array.
c                   1,n  bottom of duct 'n', meters.
c                   2,n  top of duct 'n', meters.
c                   3,n  minimum refractivity of duct 'n', M-units.
c    lvls         Number of refractivity level in rmu, rhts.
c    ndcts        in:  the maximum number of ducts allowed.
c                 out: the number of ducts found.
c    nq           Duct counter.
c    rht          Height array, meters.
c    rmu          Modified refractivity, M-unit array, elements
c                   correspond to like-number elements of rht array.
c
c
```

```
      SUBROUTINE ducts(rmu,rht,lvls,DCT,NDCTS)
c
      real*4 dct,delu,delh,deltu,hbot,htop,rht(32),rmu(32)
      integer*2 lvls,ibot,iduct,iend,iq,itop,ndcts,nq
      dimension dct(3,8)
c
c       Locate all major ducts
      nq=0
      iq=3*ndcts
      itop=lvls
      iend=ndcts
      ndcts=0
      DO iduct=1,iend
c
c           Look for top of next duct
 1010     continue
          htop=rht(itop)
          if(itop.eq.1) go to 1060
          ibot=itop-1
          if(rmu(itop).le.rmu(ibot)) go to 1020
          itop=itop-1
          go to 1010
c
c           Look for bottom of the duct
 1020     continue
          hbot=rht(ibot)
          if(rmu(ibot).lt.rmu(itop)) go to 1030
          if(ibot.eq.1) go to 1040
          ibot=ibot-1
          go to 1020
c
c           Calculate bottom of duct using linear interpolation
 1030     continue
          delu=rmu(ibot+1)-rmu(ibot)
          delh=rht(ibot+1)-rht(ibot)
          deltu=rmu(itop)-rmu(ibot)
          if(delu.lt.0.01) go to 1040
          hbot=rht(ibot) + deltu*delh/delu
c
c           Store duct parameters in array dct
 1040     continue
          amu=rmu(itop)
          call push(dct,iq,nq,amu)

          call push(dct,iq,nq,htop)
          call push(dct,iq,nq,hbot)
          ndcts=iduct
          itop=ibot
      END DO
c
 1060 continue
      RETURN
      END
```

```
c
c  Subroutine envfil
c
c  ENVFIL lists the available environmental files and allows the
c  user to select one.  The selected environmental file is read
c  and closed.  The data from the file is returned to the calling
c  routine.
c
c  Variable:        Description:
c    delta          Evaporation duct height in m.
c    height         Array of up to 30 elements containing the heights
c                     of the M-unit profile.
c    levels         The number of levels in the height, Munits arrays.
c    Munits         Array of up to 30 elements containing the M-unit
c                     values of the upper-air profile.
c    wind           Wind speed in knots.
c
c
      SUBROUTINE envfil(delta, height, Munits, wind, levels)
c
c
      real*4 delta, height(30), Munits(30), wind
      integer*2 levels, ZR, ZW
      character*12 filename
c
c     Initialize read, write channels
      ZR = 5
      ZW = 6
c
      write (ZW,'(" Available Environmental Files: ")')
c       List all files beginning with "E".
      call system ('ls [E]* 1>&2'//char(0))
      write (ZW,'(//,"Enter input file name: ",$)')
      read (ZR,'(a12)') filename
      open (10,FILE=filename)
c
c       Read wind speed in knots and evaporation duct height in m.
      read (10, '(f4.1)') delta
      read (10, '(f4.1)') wind
c       Read the number of levels in M-unit profile.
      read (10, '(i2)') levels
c       Read the height and M-unit profile array values.
      DO i=1, levels
         read (10, '(2f10.1)') height(i), Munits(i)
      END DO
c       Close environmental file.
      close(10)
c
      RETURN
      END
```

```
c
c  Subroutine envinp
c
c  Subroutine ENVINP prompts the user to enter environmental parameters
c  and returns.  Environments can be entered over the keyboard or from
c  a file.  If the environment is entered over the keyboard it can be
c  saved in a file for future use.
c
c  Variable:         Description:
c    delta          Evaporation duct height in m.
c    height         Array of up to 30 elements containing the heights
c                     of the M-unit profile.
c    levels         The number of levels in the height, Munits arrays.
c    Munits         Array of up to 30 elements containing the M-unit
c                     values of the upper-air profile.
c    wind           Wind speed in knots.
c
c
      SUBROUTINE envinp(DELTA, HEIGHT, MUNITS, WIND, LEVELS)
c
      real*4 delta, height(30), Munits(30), wind
      character*20 A, dummy, filename
      integer*2 k, kt, levels, ZW, ZR
c
c       Specify the read (5) and write (6) channel numbers.
      ZW = 6
      ZR = 5
c       Initialize environmental parameters.
      wind = 0.0
      delta = 0.0
      levels = 2
      DO i = 1,30
        height(i) = 0.0
        Munits(i) = 0.0
      END DO
c       Enter the environmental data parameters.
      write(ZW,'("Enter environmental data parameters. You may enter")')
      write(ZW,'("up to 30 layers or enter data from a file.  ")')
c
c       Select environmental file.
      write(ZW,'("Enter data from a file? (yes or no) ",$)')
      read(zr,'(A)')dummy
      IF ((dummy(1:1) .eq. 'y').or.(dummy(1:1) .eq. 'Y')) THEN
        call envfil(delta, height, Munits, wind, levels)
      ELSE
        write(ZW,'("Adjcent layers must have different M-values and")')
        write(ZW,'("at least two layers are required.")')
c
        height(1) = 0.0
        Munits(1) = 0.0
        write(ZW,1000)
 1000   format(/,'Enter M-unit Profile - (Height in meters, M-units)'
     1        /,'Starting height is at surface (0 meters) ')
c
c   DO loop to enter profile data (Height and Munit arrays).
c
        DO i = 1, 30
  100     write(zw,'(" Enter height in meters (or end) ",$)')
          read(zr,'(A)')dummy
          IF ((dummy(1:1) .EQ. 'e').OR.(dummy(1:1) .EQ. 'E')) goto 200
          k = 1
          kt = 1
          DO WHILE((kt .eq. 1) .and. (k .le. 20))
            IF (dummy(k:k).EQ.' ') dummy(k:k) = '.'
```

```
      IF (dummy(k:k).EQ.'.') kt = 0
      k = k + 1
    END DO
    IF (i .gt. 1) THEN
      read(dummy,'(f10.2)')height(i)
      IF (height(i) .LE. height(i-1)) THEN
        write(zw,1010)
1010    format('Heights must increase, re-enter height ')
        goto 100
      END IF
    END IF
    levels = i
    write(zw,'(" Enter M-unit value at level ",$)')
    read(zr,'(A)')dummy
    k = 1
    kt = 1
    DO WHILE((kt .EQ. 1) .AND. (k .LE. 20))
      IF (dummy(k:k).EQ.' ') dummy(k:k) = '.'
      IF (dummy(k:k).EQ.'.') kt = 0
      k = k + 1
    END DO
    read(dummy,'(f10.2)')Munits(i)
    IF ((i .NE. 1) .AND. (Munits(i) .EQ. Munits(i-1))) THEN
      Munits(i) = Munits(i) + 0.1
    END IF
  END DO
200  continue
  write(ZW,1020)
c
1020 format('Enter evaporation duct height in meters (0 to 40) ',$)
  read(ZR,*) delta
  IF (delta .LT. 0.0) delta = 0.0
  IF (delta .GT. 40.0) delta = 40.0
c
  write(ZW,1030)
1030 format('Enter wind speed in knots (0 to 50) ',$)
  read(ZR,*) wind
  IF (wind .LT. 0.0) wind = 0.0
  IF (wind .GT. 50.0) wind = 50.0
c
  write(ZW,'("Do you wish to store this environment in a file?",
 1  " (yes or no) ",$)')
  read(zr,'(A)')dummy
  IF ((dummy(1:1) .eq. 'y').or.(dummy(1:1) .eq  'Y')) THEN
    write (ZW,'(" Current Environmental Files: ")')
    call system ('ls [E]* 1>&2'//char(0))
    write (ZW, 1040)
1040  format("Enter file name (First letter MUST be E) ",$)
    read (ZR,'(a12)') filename
    open (10,FILE=filename)
c
c    Write wind speed in knots and evaporation duct height in m.
    write(10, '(f4.1)') delta
    write(10, '(f4.1)') wind
c    Write the numbers of levels in M-unit profile.
    write(10, '(i2)') levels
    DO i=1, levels
       write(10, '(2f10.1)') height(i), Munits(i)
    END DO
c      close file
    close(10)
  END IF
c
 END IF
```

```
c
      RETURN
      END
```

```
c
c  Subroutine getk
c
c  Subroutine GETK is used to determine the effective earth radius
c  factor k.  Getk accomplishes this by tracing a ray from the trans-
c  mitter height to 200 NMi (370 km).  The ray launch angle is 0 deg.
c  if no surface-based duct exists, or alphac, the critical angle if
c  one does.
c
c  Variable:         Description:
c    alphac        Critical angle necessary to escape duct.  If alphac
c                    = 0 then no surface-based duct exists.
c    a0            Initial ray launch angle, radians.
c    a1            Ray angle at top of layer, radians.
c    deld          Range difference, km.
c    delh          Height difference, meters.
c    delM          M-unit difference.
c    delmdh        M-unit gradient.
c    dMdh          M-unit gradient array.
c    hlast         Height at 370 km.
c    hmrs          Array of height elements, in meters.
c    ntot          Maximum number of elements in hmrs and dMdh arrays.
c    rdeld         Range incremented in ray trace.
c    rmax          Maximum range for ray trace = 370 km.
c    rng           Range, km.
c    rk            Effective earth radius factor.
c    xmtr          Transmitter height in meters.
c
      SUBROUTINE getk(alphac, dMdh, hmrs, ntot, xmtr, RK)
c
      real*4 alphac, a0, a1, deld, delh, delM, delmdh, dMdh(32)
      real*4 hlast, hmrs(32), rdeld, rmax, rng, rk, xmtr
      integer*2 ntot, i
c
      rmax = 370.0
      h = xmtr
      rng = 0.0
      a0 = alphac
c        Loop to trace ray through the atmospheric layers.
      DO i=2,ntot-1
        delm = (hmrs(i+1) - h)*dMdh(i)*1.0E-3
        a1 = SQRT(a0*a0 + 2.0*delm)
        deld = (a1 -a0)/dMdh(i)
        rdeld = rng + deld
        IF(rdeld .GT. rmax) GOTO 1000
        a0 = a1
        h = hmrs(i+1)
        rng = rdeld
      END DO
      i = ntot
 1000 continue
c        Ray trace in final layer to range rmax.
      deld = rmax - rng
```

```
      a1 = a0 + dMdh(i) * deld
      delM = (a1*a1 - a0*a0)*0.5
      delh = 1000.0*delM/dMdh(i)
      hlast = hmrs(i) + delh
c       Determine the equivalent single-gradient atmosphere that
c       would be required to trace a ray launched at alphac that
c       would arrive at height = hlast at a range of 370 km.
      delmdh = (-alphac)*2.0/rmax + 2.0E-3*(hlast - xmtr)/(rmax*rmax)
      rk = 1.0/(6371.0 * delmdh)
      IF(rk .GT. 5.0) rk = 5.0
      IF(rk .LE. 0.5) rk = 0.50

      RETURN
      END
```

```
c
c   Subroutine gtheta
c
c   GTHETA calculates optical phase-lag difference angle 'theta'
c   between direct and sea-reflected rays using the reflection
c   point range 'r1'
c
c   Variable:          Description:
c     ae2              Effective earth radius * 2000.
c     h1               Height of transmitting antenna, m.
c     h2               Height of receiver/target, m.
c     h1p              Effective height of h1, m.
c     h2p              Effective height of h2, m.
c     plr              Antenna polarization: H = horizontal
c                                            V = vertical
c                                            C = circular
c     psi              Grazing angle in radians.
c     phi              Phase lag due to reflection, radians.
c     r                Total ground range, km.
c     r1               Reflection point range, (from h1), km.
c     r2               Reflection point range, (from h2), km.
c     rmag             Magnitude of the reflection coefficient.
c     theta            Total phase lag between direct and reflected
c                      rays including phi.
c
      SUBROUTINE gtheta(plr,r1,R,THETA,R2,PSI,RMAG)
c
c
      real*4  h1p, h2p, psi, phi, r, r1, r2, rmag, theta
      character*1 plr
c
      include 'ffac.common'
      include 'envsys.common'
c
      h1p = h1 - r1*r1/ae2
      psi = 1.0e-3 * h1p/r1
      IF (psi .GT. 0.03) psi = ATAN(1.0e-3 * h1p/r1)
c       Ray trace equation used to determine r2 based on psi.
      r2 = ( SQRT(psi*psi + 2.0e-3 * h2/ae) - psi ) * ae
      r = r1 + r2
      h2p = h2 - r2*r2/ae2
      call ref(plr,psi,RMAG,PHI)
```

```
c       Calculate theta = Path-length difference + phase lag due
c         to reflection (phi).
        theta = phi + thefac*h1p*h2p / r
        RETURN
        END
```

```
c
c   Subroutine hgain
c
c   HGAIN returns a height-gain factor in dB for a specified height.
c
c   Variable:        Description:
c     c1 - c7        Constants used to calculate fzdb for evap. ducts.
c     del            Scaled evaporation duct height.
c     delta          Evaporation duct height, m.
c     freq           EM system frequency in MHz.
c     fzdb           Height-gain factor in dB.
c     h              The height for whi·n the height-gain factor is
c                      required, m.
c     hmin           Minimum height.
c     sbdht          Surface-based duct height, m.
c     rfac           Evaporation duct range scale factor.
c     zfac           Evaporation duct height scale factor.
c     zmax           Height above which different eqn.s are used for height-
                       gain calculations for del>10.25m.
c     z1             Scaled height for surface-based ducts.
c     z2             Scaled height for evaporation duct heights.
c
        SUBROUTINE hgain (h, FZDB)
c
        real*4 fzdb, h, z1, z2
c
        include 'ffac.common'
        include 'envsys.common'
c
        fzdb = 0.0
        IF (sbdht .GT. 0.0) THEN
c             Calculate surface-based duct height-gain factor.
          z1 = h / sbdht
          IF ((Freq .LE. 150.0).AND.(z1 .LT. 0.8)) THEN
            fzdb = -60.0 * (z1 - 0.5)**2
          END IF
          IF ((Freq .LE. 150.0).AND.(z1 .GE. 0.8)) THEN
            fzdb = 1.14 * z1**(-6.26) - 10.0
          END IF
          IF ((Freq .GT. 150.0).AND.(z1 .LT. 1.0)) THEN
            fzdb = 10.0 - 200.0 * (z1 - 0.5)**4
          END IF
          IF ((Freq .GT. 150.0).AND.(Freq .LE. 350.0)
       1                              .AND.(z1 .GE. 1.0)) THEN
             fzdb = 7.5 * z1**(-13.3) - 10.0
          END IF
          IF ((Freq .GT. 350.0).AND.(z1 .GE. 1.0)) THEN
            fzdb = 12.5 * z1**(-8.0) - 15.0
          END IF
        ELSE
```

```
c          Calculate evaporation duct height-gain factor.
         z2 = AMAX1(h * zfac, hmin)
         IF (Del .GE. 10.25) THEN
c             Calculate height-gain for del>=10.25 meters.
           IF (z2 .GT. zmax) THEN
             fzdb = c5 * (z2**c6) + c7
           ELSE
             fzdb = c1 * ALOG(SIN(c2 * (z2**c3))) + c4
           END IF
         ELSE
c             Calculate height-gain for del<10.25 meters.
           fzdb = (c1 * z2**c2) + (c3 * z2**c4) + c5
         END IF
       END IF

       RETURN
       END
```

```
c
c   Subroutine insrt
c
c   INSRT inserts (or appends) a new level into the M-unit profile.  It
c   does this by locating the  new height relative to the existing pro-
c   file heights.  If the new height is greater than the top level, then
c   append a new level for the new height.  If the new height is between
c   two levels, then insert a new level for the new height.  If the new
c   height is equal to an existing level's height, do not add a new
c   level for the new height.
c
c   Variable:          Description:
c     amu            Modified refractivity array, M-units.
c     hmrs           Height array, meters, each element corresponding to
c                      the like-number amu array element.
c     iq             Number of levels in amu and hmrs.
c     hgt            Height of new level to be added, meters.
c     ipnt           Index pointer to new level.
c
c
      SUBROUTINE insrt(amu,hmrs,iq,hgt,ipnt)
c
      real*4 amu(32),hmrs(32),hgt
      integer*2 iq,ipnt
c
      DO i=1,iq
         ilevel=i
         IF(ABS(hgt-hmrs(ilevel)).LE.0.01) go to 1020
         IF(hmrs(ilevel).GT.hgt) go to 1030
      END DO
c
c         Hgt > amu(iq)
      iq=iq+1
      ipnt=iq
      grdnt=0.1181102
      amu(ipnt)=amu(iq-1) + (hgt-hmrs(iq-1))*grdnt
      hmrs(ipnt)=hgt
      go to 1050
```

```
c
c        Hgt = hmrs(ilevel)
 1020 continue
      ipnt=ilevel
c     amu(ipnt)=amu(ilevel)
      hmrs(ipnt)=hgt
      go to 1050
c
c        Hmrs(ilevel) > hgt > hmrs(ilevel-1)
 1030 continue
c        Shift levels above new height up one
      DO i=ilevel,iq
         j=iq - (i-ilevel)
         hmrs(j+1)=hmrs(j)
         amu(j+1)=amu(j)
      END DO
      iq=iq+1
      ipnt=ilevel
      grdnt=(amu(ipnt+1)-amu(ipnt-1))/(hmrs(ipnt+1)-hmrs(ipnt-1))
      amu(ipnt)=amu(ipnt-1) + (hgt-hmrs(ipnt-1))*grdnt
      hmrs(ipnt)=hgt
c     go to 1050
c
 1050 continue
      RETURN
      END
```

```
c
c  Subroutine mprof
c
c  MPROF modifies the M-unit and height arrays  by inserting a level at
c  the antenna height using straight line interpolation (or a standard
c  atmosphere gradient) to calculate its M-unit value.  The new profile
c  is then used to locate any ducts that might be contained in the pro-
c  file.  If the bottom of the duct is below the EM system antenna
c  height, and the top above the antenna height, then a critical angle
c  is calculated for the EM system in the surface-based duct.  (It is
c  assumed that low-elevated ducts are surface ducts if the EM system is
c  in the duct.)
c
c  Variable:        Description:
c    alphac        The critical penetration angle necessary to escape duct
c    amu           An array of M-unit values
c    antena        EM system antenna height
c    antmu         M-unit value at the EM system antenna height
c    dcts          24  duct parameter array
c                      1,n  bottom of duct 'n', meters
c                      2,n  top of duct 'n', meters
c                      3,n  minimum refractivity of duct 'n', m-units
c    dMdh          M-unit gradient array
c    hbot          Height of the bottom of a duct
c    htop          Height of the top of a duct
c    height        Height array with the original profile heights
c    hmrs          Height array with elements corresponding to the dMdh
c                    array elements
c    lvlant        EM system antenna level
c    lvltop        Maximum number of layers in the hmrs array
```

```
c     Munits       M-unit array with elements corresponding to the height
c                    array elements
c     ndcts        The number of ducts stored in 'dcts'
c     nmax         The number of elements in the height and Munit arrays
c     ntot         The number of elements in the dMdh and hmrs arrays
c     rma          M-unit value at the minimum on the duct profile
c     sbdht        The height of the surface-based duct
c
c     Variables not listed are temporary variables.
c
c

      SUBROUTINE mprof(height,Munits,antena,nmax,ALPHAC,DMDH,HMRS,
     1                    SBDHT,NTOT)

c
c
      real*4 alphac,amu(32),antena,dmdh(32),hmrs(32),height(30)
      real*4 Munits(30),sbdht
      real*4 antmu,dcts,hb,ht,rma
      integer*2 lvlant,lvltop,nmax,ntot
      integer*2 ndcts
      dimension dcts(3,8)
c
      lvltop = nmax
      alphac = 0.0
      sbdht = 0.0
c
c       Copy height and m-unit arrays.
c
      lvltop = nmax
      DO i = 1, nmax
         hmrs(i)=height(i)
         amu(i)=Munits(i)
      END DO
c
c       Insert new level at the antenna height.
c
      call insrt(amu,hmrs,lvltop,antena,lvlant)
      antmu=amu(lvlant)
c
c       Locate all major ducts.
      ndcts=8
      call ducts(amu,hmrs,lvltop,dcts,ndcts)

c
c       Define trapping duct parameters.
      IF(ndcts .NE. 0)THEN
        DO iduct=1,ndcts
          hb=dcts(1,iduct)
          ht=dcts(2,iduct)
          rma=dcts(3,iduct)
          IF((antena .GT. hb) .AND. (antena .LT. ht)) go to 1040
          IF(hb.lt.0.01) go to 1040
        END DO
      END IF
c
c       Antenna not inside a major duct.
      go to 1050
```

```
c
c        The antenna is inside a low-level elevated duct
c           or inside a surface-based duct.
 1040    continue
      sbdht = ht
      alphac=1.0e-3*sqrt(2.0*(antmu-rma)) + 1.0e-5
 1050 continue
c
c     Delete all levels between the surface and the antenna level.
      DO i = lvlant,lvltop
         j=i-(lvlant-2)
         hmrs(j)=hmrs(i)
         amu(j)=amu(i)
      END DO
      lvltop=j
      lvlant=2
c
c       Calculate the M-unit gradient array.
      iend=lvltop-1
      DO i = 1, iend
         delu=amu(i+1)-amu(i)
         delh=hmrs(i+1)-hmrs(i)
         dmdh(i)=1.0e-3*delu/delh
      END DO
      dmdh(lvltop)=0.1181102e-3
c
      ntot = lvltop
      RETURN
      END
```

```
c
c  Subroutine opcnst
c
c  OPCNST initializes optical region constants.
c
c  Variable:        Description:
c    ae            Effective earth radius, (rk * 6371), km.
c    aeth          Effective earth radius * 1000.
c    ae2           Aeth * 2
c    eps           Dielectric constant of sea-water, epsilon.
c    freq          EM system frequency in MHz.
c    fsterm        Free-space loss constant in dB.
c    hbar          RMS wave height due to wind in m.
c    hbfreq        Constant for subroutine ruff,
c                    (hbar * 2 * PI / wavelength).
c    polar         EM system antenna polarization:
c                    H = horizontal, V = vertical, C = circular
c    rk            Effective earth radius factor.
c    rnreal        Real part of the square of the index of refraction.
c    rnimag        Imaginary part of the square of the index of refract.
c    thefac        Constant used to calculate path-length difference
c                    between direct and sea-reflected rays.
c    twoae         Constant (ae * 2).
c    wind          Wind speed in kts.
c
c
```

```
      SUBROUTINE opcnst
c
c
      real*4 eps, sigma
c
      include 'ffac.common'
      include 'envsys.common'
c
      fsterm = 32.44 + 20.0 * ALOG10(freq)
c         Exclusively for REF subroutine
      IF (polar .NE. "H") THEN
c           eps is the permittivity of salt water
c           sigma is the conductivity of salt water
        IF (freq .LE. 1500.0) THEN
          eps = 80.0
          sigma = 4.3
        ELSEIF (freq .LE. 3000.0) THEN
          eps = 80.0 - 0.00733 * (freq - 1500.0)
          sigma = 4.3 + 0.00148 * (freq - 1500.0)
        ELSEIF (freq .LE. 10000.0) THEN
          eps = 69.0 - 0.00243 * (freq - 3000.0)
          sigma = 6.52 + 0.001314 * (freq - 3000.0)
        ELSE
          eps = 51.99
          sigma = 15.718
        END IF
c         Define the real and imaginary parts of the square of
c         the index of refraction of sea-water.
        rnreal = eps
        rnimag = (-18000.0) * sigma/freq
      END IF
c        Define rms wave-height for subroutine RUFF
      hbar = 0.0051 * (0.51477*wind)**2
      hbfreq = 0.02094 * freq * hbar
c
      ae = rk * 6371.0
      twoae = 2.0 * ae
      aeth = rk * 6.371
      ae2  = aeth * 2.0
      thefac = freq * 4.193E-5
c
      RETURN
      END
```

```
c
c   Subroutine opffac
c
c   OPFFAC calculates quantities used to determine the pattern
c   propagation factor (F) in the optical interference region.
c
c   Variable:         Description:
c     ae            Effective earth radius, km.
c     alpha         Direct ray launch angle, radians.
c     angle         Angle for which antenna pattern factor desired.
c     beta          Reflected ray launch angle, radians.
c     divfac        Divergence factor.
c     dr            Constant - product of antenna pattern factor for
c                     reflected ray * divergence factor * reflection
c                     coefficient * surface roughness factor.
c     gamma         Earth's interior angle (r1/ae).
c     psi           Grazing angle, radians.
c     r1            Reflection point range, km.
c     r2            Reflection point range, km.
c     range         Total ground range in km.
c     rmag          Magnitude of reflection coefficient.
c     ruf           Sea-surface roughness coefficient.
c     sinpsi        Sin(psi).
c     twoae         2*ae
c
c
      SUBROUTINE opffac(gamma,range,psi,r1,r2,rmag,ELANG,DPAT,DR)
c
      real*4 angle, beta, divfac, dpat, dr, elang, gamma, psi, r1,
     1       r2, range, rmag, ruf, sinpsi
c
      include 'ffac.common'
      include 'envsys.common'
c
      patfac = 1.0
c       Calculate direct ray launch angle, alpha.
      alpha = hdif/range - range/twoae
      angle = alpha
      elang = alpha
c       Determine antenna pattern factor for direct ray alpha.
      call antpat(antype,alpha,antbwr,antelr,antfac,
     1                                       patrfac,angle,PATFAC)
      patd = patfac
      dpat = patfac
      beta = - (gamma + psi)
      angle = beta
c       Determine antenna pattern factor for reflected ray beta.
      call antpat(antype,alpha,antbwr,antelr,antfac,
     1                                       patrfac,angle,PATFAC)
c       Determine surface roughness coefficient.
      sinpsi = SIN(psi)
      call ruff(hbar, hbfreq, psi, sinpsi, RUF)
c       Calculate the divergence factor.
      divfac = 1.0/(SQRT(1.0 + (2.0 * r1 * r2)/(ae * range * sinpsi)))
      dr = patfac * ruf * divfac * rmag
c
      RETURN
      END
```

```
c
c  Subroutine oplimit
c
c  OPLIMIT calculates the maximum range in the optical region, opmaxd,
c  and opmaxl = -20 LOG(F) at opmaxd, where F is the pattern propagation
c  factor.
c
c  Variable:       Description:
c    ae           Effective earth radius, km.
c    ae2          ae * 2000
c    alpha        Direct ray launch angle, radians.
c    alphac       Critical angle in radians.
c    al           An angle used to determine rl(psilim).
c    exloss       A measure of how much of the antenna's energy
c                   is directed toward the horizon, dB.
c    freq         EM system frequency, MHz.
c    fsqrd        Square of the pattern propagation factor, F.
c    gamma        Earth's interior angle.
c    hdif         Difference in height between hl and h2.
c    horznl       Tangent ray distance for height hl, km.
c    hl           Transmitter height, m.
c    hlp          Effective transmitter height, m.
c    h2           Receiver/target height, m.
c    h2p          Effective receiver/target height, m.
c    opmaxd       Maximum range in optical region, km.
c    opmaxl       Propagation factor in dB at opmaxd.
c    pd           Path-length difference between direct and
c                   sea-reflected rays.
c    phi          Phase lag due to reflection from sea-surface.
c    psilim       Grazing angle limit to optical region.
c    psi          Grazing angle in radians.
c    r            Total ground range, km.
c    rl           Reflection point range (from hl), km.
c    r2           Reflection point range (from h2), km.
c    rk           Effective earth radius factor.
c    theta        Total phase difference between direct and sea-reflected
c                   rays (pd) and phase-lag due to reflection, phi.
c    thefac       Constant used to calculate path-lenght difference.
c    thnext       The next value of theta to be determined.
c
c
      SUBROUTINE oplimit(OPMAXD,OPMAXL)
c
      real*4 al, dr, fsqrd, gamma, halfpi, hlp, h2p, pd, phi,
     1       pi, psi, psilim, r, rl, r2, rmag, theta, thnext
c
      include 'ffac.common'
      include 'envsys.common'
c
      PI = 3.14159
      halfpi = PI / 2.0
      horznl = 3.572 * SQRT(rk * hl)
      psilim = 0.01957/(freq*rk)**0.33333
c       If both terminals are in the duct set alphac = 0.0
      IF ((alphac .GT. 0.0) .AND. (h2 .LT. sbdht)) alphac = 0.0
c       Initial guess for rl is based on grazing angle limit range.
c       Use ray trace equations to determine rl and r2.
      psi = psilim
      al = SQRT(psi**2 + 2.0e-3*hl/ae)
      rl = (al - psi)*ae
      r2 = rl
      IF (h2 .GT. hl)r2 = r2 + (SQRT(al**2 + 2.0*ABS(hdif)/ae) - al)*ae
      r = rl + r2
      hlp = hl - rl*rl/ae2
```

```
      h2p = h2 - r2*r2/ae2
      call ref(polar,psi,RMAG,PHI)
      pd = thefac*h1p*h2p / r
c
c       Calculate theta based on grazing angle limit.
c
      theta = phi + pd
      alpha = hdif/r - r/twoae
      IF (alphac .GT. 0.0) THEN
        IF ((alpha .LT. alphac) .OR. (pd .GT. halfpi)) THEN
c
c           Calculate theta based on range obtained from alphac.
c
          r = (SQRT(alphac**2 + 2.0*ABS(hdif)/ae) - alphac)*ae
          call opticf(polar,r,PD,PSI,THETA,FF)
        END IF
      END IF
      IF ((alphac .GT. 0.0) .AND. (pd .GT. halfpi)) THEN
c
c       If theta>(2 Pi) then optical limit is 1st peak
c       with theta greater than theta(alphac).
c
        IF (theta .GT. 6.28319) THEN
          thnext = INT(theta/(2.0*PI) + 1)*(2.0 * PI)
          call r1iter(polar,thnext,R1,R2,R,PSI,RMAG)
          theta = thnext
        END IF
      ELSE
c
c       Optical limit is grazing angle limit or 1/4 wavelength limit.
c
        IF ((pd .GT. halfpi) .OR. (psi .NE. psilim)) THEN
c
c       Determine theta value @ 1/4 wavelength limit, (H polar).
c
          thnext = 1.5 * PI
          call r1iter("H",thnext,R1,R2,R,PSI,RMAG)
          IF (polar .NE. "H") THEN
            call ref(polar,psi,RMAG,PHI)
            theta = halfpi + phi
          ELSE
            theta = thnext
          END IF
        END IF
      END IF
      IF (ht .GE. hr) THEN
        gamma = r2/ae
      ELSE
        gamma = r1/ae
      END IF
      call opffac(gamma,r,psi,r1,r2,rmag,ALPHA,PATD,DR)
      fsqrd = (patd*patd + dr*dr + 2.0*dr*patd*COS(theta))
c       Limit fsqrd to prevent runtime errors when taking LOG(fsqrd).
      IF (fsqrd .LT. 1.0e-7) fsqrd = 1.0e-7
      opmaxd = r
      opmaxl = - 10.0 * ALOG10(fsqrd)
      exloss = - 20.0 * ALOG10(patd)
      RETURN
      END
```

```
c
c  Subroutine opticf
c
c  Subroutine OPTICF calculates the total phase difference, theta,
c  between direct and sea-reflected ray paths, including phase
c  change due to reflection from sea-surface.  It then uses theta
c  to determine the value of the pattern propagation factor, F, in
c  the optical region, and returns 20Log(F).
c
c
c  Variable:      Description:
c    ae           Effective earth radius, km.
c    ae2          Ae*2000, km.
c    aeth         Ae*1000, km.
c    alpha        Direct ray launch angle, radians.
c    dr           Product of divergence factor, surface roughness
c                   coefficient, reflection coefficient and antenna
c                   pattern factor for the reflected ray.
c    epsr         Iteration loop range tolerance, km.
c    ff           Pattern propagation factor, F, in dB.
c    fprl         Value of the derivative of the cubic equation at rl.
c    frl          Value of the cubic equation for a given rl.
c    fsqrd        Square of the pattern propagation factor.
c    gamma        Earth's interior angle (rl/ae) in radians.
c    hrp          Effective receiver/target height, m.
c    htp          Effective transmitter height, m.
c    hl           The transmitter height, m.
c    h2           The receiver/target height, m.
c    pd           The path-length difference between direct and re-
c                   flected rays in radians.
c    phi          Phase lag due to reflection from sea surface, rad.
c    psi          Grazing angle in radians.
c    r            Total ground range, km.
c    rl           Reflection point range, (from xmtr), km.
c    rlsqrd       Square of the reflection point range.
c    r2           Reflection point range, (from rcvr/target), km.
c    rr           Iteration loop variable - range difference.
c    rmag         Magnitude of reflection coefficient.
c    t            Iteration loop variable.
c    theta        Total phase lag between direct and sea-reflected
c                   rays, in radians.  (theta = pd + phi)
c    thefac       Constant used to calculate theta.
c    v            Iteration loop variable.
c    w            Iteration loop variable.
c
c
      SUBROUTINE opticf(plr,r,PD,PSI,THETA,FF)
c
      real*4 dr, epsr, ff, frl, fprl, fsqrd, gamma, hrp, htp,
     1       phi, psi, r, rl, rlsqrd, r2, rmag, rr, t, theta, v, w
      character*1 plr
      integer*2 jk
c
      include 'ffac.common'
      include 'envsys.common'
c
      rl = (hl/(hl + h2))*r
      t = -1.5 * r
      v = 0.5 * r * r - aeth * (hl + h2)
      w = aeth * r * hl
      epsr = 0.050
      rr = 2.0 * epsr
      jk = 1
c
```

```
c       WHILE ((jk .LT. 10).AND.(abs(rr) .GT. epsr))
c
c         Use Newton-Raphson iteration to solve Kerr's cubic equation
c         for reflection point range of the sea-reflected ray.  (This
c         equati.n may be solved explicitly using an inverse cosine.)
c         The Newton iteration works best if h1 is less than h2.
c
        DO WHILE ((jk .LT. 10).AND.(abs(rr) .GT. epsr))
          jk = jk + 1
          r1sqrd = r1 * r1
c           Kerr's cubic equation for reflection point range.
          fr1 = r1*r1sqrd + t*r1sqrd + v*r1 + w
c           Derivative of the cubic equation.
          fpr1 = 3.0*r1sqrd + 2.0*t*r1 + v
          rr = fr1/fpr1
          r1 = r1 - rr
          IF ((r1 .LT. 0.0).OR.(r1 .GT. r)) r1 = r/2.0
c       WEND
        END DO
        r2 = r - r1
        htp = h1 - r1*r1/ae2
        hrp = h2 - r2*r2/ae2
        psi = 1.0e-3 * htp / r1
        IF (psi .GT. 0.3) psi = ATAN(1.0e-3 * htp/r1)
        call ref(plr,psi,RMAG,PHI)
        pd = thefac*htp*hrp/r
        theta = pd + phi
        IF (ht .GE. hr) THEN
          gamma = r2/ae
        ELSE
          gamma = r1/ae
        END IF
        call opffac(gamma,r,psi,r1,r2,rmag,ALPHA,PATD,DR)
        fsqrd = patd*patd + dr*dr + 2.0*dr*patd*COS(theta)
c         Limit F-factor to -70 dB.
        IF (fsqrd .LT. 1.0e-7) fsqrd = 1.0e-7
        ff = - 10.0 * ALOG10(fsqrd)
c
        RETURN
        END
```

```
c
c  Subroutine push
c
c  PUSH stores elements in an array and returns.
c
c  Variable:        Description:
c
c    array        iq array to hold data elements
c    iq           Size of data array
c    nq           Number of data elements stored in data array
c    data         The data element to be stored
c
c
      SUBROUTINE push(ARRAY,iq,nq,data)
c
      real*4 data,array
      integer*2 iq,nq
      dimension array(iq)
c
c       Shift array elements down one
c     do i=iq,2,-1
      DO j=2,iq
         i=iq-(j-2)
         array(i)=array(i-1)
      END DO
c
c       Store new data element in top of array
      array(1)=data
      nq=nq+1
      IF(nq .GT. iq) nq = iq
      RETURN
      END
```

```
c
c  Subroutine rliter
c
c  RlITER determines a reflection point range 'rl' corresponding
c  to 'rtheta'.  The desired reflection point range is determined by
c  a Newton-Raphson iteration technique to vary the reflection point
c  point range until the correct value is found.
c
c  Variable:         Description:
c    r            Distance, or range, in km.
c    rl           Distance from the transmitting antenna to reflection
c                   point in km.
c    r2           Distance from the target/receiver antenna to the
c                   reflection point in km.
c    f            Function (Total path difference between direct and
c                   sea-reflected rays: Theta) used in iteration loop.
c    fl           Finite derivative of f.
c    irlmda       Iteration loop counter.
c    phi          Phase-lag due to sea-surface reflection - radians.
c    plr          EM system polarization [H = horizontal, V = vertical,
c                   C = circular].
c    psi          Grazing angle in radians.
c    r            Range, in km.
```

```
c     r1           Distance from the transmitting antenna to reflection
c                    point in km.
c     r2           Distance from the target/receiver antenna to the
c                    reflection point in km.
c     rmag         Magnitude of the reflection coefficient.
c     rtheta       The desired value of theta.
c
c
      SUBROUTINE rliter(plr,rtheta,R1,R2,R,PSI,RMAG)
c
c
      real*4  f, f1, phi, psi, r, r1, r2, rmag, rr, rtheta
      character*1 plr
      integer*2 irlmda
c
      include 'ffac.common'
      include 'envsys.common'
c
      irlmda = 0
      rr = r1
c
c     WHILE ((abs(rr) .GT. 0.001).AND.(irlmda .LT. 100))
c       (Equivalent to: 100 IF ((...).and.(...)) THEN
c                             ...
c                             GOTO 100
c
      DO WHILE ((abs(rr) .GT. 0.001).AND.(irlmda .LT. 100))
c
c         Calculate phase difference, theta, corresponding to
c         reflection point range r1.  Then use finite derivative
c         method to iterate to the range where theta is equal to
c         the target value: rtheta.
c
        call gtheta(plr,r1,R,F,R2,PSI,RMAG)
        call gtheta(plr,r1+0.001,R,F1,R2,PSI,RMAG)
        fp = (f1 - f) / 0.001
        rr = (rtheta - f) / fp
        irlmda = irlmda + 1
        IF (rr .GT. -r1) THEN
          IF (rr + r1 .LE. horznl) THEN
            r1 = r1 + rr

          ELSE
            r1 = (r1+horznl)/2.0
          END IF
        ELSE
          r1 = r1/2.0
        END IF
      END DO
c     WEND
      RETURN
      END
```

```
c
c  Subroutine ref
c
c  Subroutine REF returns the magnitude and phase lag of the reflection
c  coefficient for reflection from the (smooth) sea surface.  These
c  quantities are calculated as a function of the grazing angle psi.
c  The complex square roots are done by separating the complex variables
c  into their real and imaginary parts.  No complex function calls are
c  used.
c
c
c  VARIABLE:        DESCRIPTION:
c    rnreal        Real part of the square of the index of refraction,
c                    (the dielectric constant of sea-water).
c    rnimag        Imaginary part of the square of the index of
c                    refraction (the conductivity of sea water
c                    times the wavelength times other constants).
c    phi           Phase change (lag) in radians.
c    plr           EM system antenna polarization: H - horizontal;
c                    V - vertical; C - Circular.
c    psi           Grazing angle in radians.
c    rmag          Magnitude of the reflection coefficient.
c    sinpsi        SIN(psi).
c
c    various       All variables not listed above are temporary.
c
      SUBROUTINE ref(plr, psi, RMAG, PHI)
c
      real*4 angrt, at, bt, ct, dt, phi, phiv, pi, psi,
     1       rcv, rmag, rmagrt, rtimag, rtreal,
     2       rvimag, rvreal, rx, sinpsi, x, y
      character*1 plr
c
      include 'ffac.common'
      include 'envsys.common'
c
      PI = 3.14159
c       Define RMAG, PHI for horizontal polarization.
      rmag = 1.0
      phi = PI
      IF (plr .NE. "H") THEN
c           Calculate RMAG, PHI for vertical polarization.
        sinpsi = SIN(psi)
        Y = rnimag
        X = rnreal - COS(psi)**2
        rmagrt = (x*x + y*y) ** 0.25
        angrt = ATAN(y/x) / 2.0
        rtreal = rmagrt * COS(angrt)
        rtimag = rmagrt * SIN(angrt)
        at = rnreal * sinpsi - rtreal
        ct = rnreal * sinpsi + rtreal
        bt = rnimag * sinpsi - rtimag
        dt = rnimag * sinpsi + rtimag
        rvreal = (at*ct + bt*dt) / (ct**2 + dt**2)
        rvimag = (bt*ct - at*dt) / (ct**2 + dt**2)
        rcv = SQRT(rvreal**2 + rvimag**2)
        IF (rvreal .NE. 0.0) THEN
          phiv = ATAN(rvimag/rvreal)
          IF (rvreal .LT. 0.0)  phiv = phiv + PI
        ELSE
          IF (rvimag .LT. 0.0)  phiv = -PI / 2.0
          IF (rvimag .GT. 0.0)  phiv = PI / 2.0
          IF (rvimag .EQ. 0.0)  phiv = 0.0
        END IF
```

```
        phiv = -phiv
        IF (phiv .LT. 0.0)  phiv = phiv + 2.0*PI
        rmag = rcv
        phi = phiv
        IF (plr .EQ. "C")THEN
c           Calculate RMAG, PHI for circular polarization.
          rx = SQRT(1.0 + rcv**2 + 2.0*rcv * COS(PI - phiv))
          rmag = rx/2.0
          a = rcv * SIN(phiv + PI) / rx
          a = ATAN( a/SQRT(1 - a*a) )
          phi = PI - a
          phi = -phi
          IF (phi .LT. 0.0) phi = phi + 2.0*PI
        END IF
      END IF
      RETURN
      END
```

```
c
c  Subroutine ruff
c
c  Subroutine RUFF returns the sea-surface roughness correction for
c  the magnitude of the sea-reflected ray.
c
c
c  VARIABLE:        DESCRIPTION:
c    hbar          rms wave height in meters.
c    hbfreq        (2*PI*hbar)/wavelength.
c    hfpsi         (hbar*psi)/wavelength.
c    psi           Grazing angle in radians.
c    sinpsi        SIN(psi).
c    rufco         Sea-surface roughness coefficient.
c
c
      SUBROUTINE ruff(hbar, hbfreq, psi, sinpsi, RUFCO)
c
      real*4  hbar, hbfreq, hfpsi, psi, rufco, sinpsi
c
c
      rufco = 1.0
      IF (hbar .NE. 0.0) THEN
         hfpsi = hbfreq * psi * 0.159155
         IF (hfpsi .LE. 0.11) THEN
           rufco = EXP((-2.0) * (hbfreq*sinpsi)**2)
         ELSEIF (hfpsi .LE. 0.26) THEN
           rufco = 0.5018913 - SQRT(0.2090248 - (hfpsi - 0.55189)**2)
         ELSE
           rufco = 0.15
         END IF
      END IF
      RETURN
      END
```

```
c
c  Subroutine sysfil
c
c  SYSFIL list available system files and allows the user to select an
c  EM system file.
c
c  Variable:        Description:
c    antena        Height of EM system antenna in m.
c    antype        Antenna type:
c                    O - omnidirectional
c                    S - sin(x)/x
c                    C - cosecant-squared
c                    H - generic height-finder
c    bwidth        Antenna beam width in degrees.
c    elevat        Antenna elevation angle in degrees.
c    filename      Name of System file.
c    freq          EM system frequency in MHz.
c    polar         Antenna polarization:
c                    H - horizontal
c                    V - vertical
c                    C - circular
c    rectar        Receiver/target height, m.
c
c
      SUBROUTINE sysfil(freq, antena, rectar, polar, antype, bwidth,
     1                  elevat)
c
c
      real*4 antena, bwidth, elevat, freq
      integer*2 ZR, ZW
      character*1 antype, polar
      character*20 filename
c
c       Initialize read and write channels.
      ZR = 5
      ZW = 6
c
      call system ('ls [S]* 1>&2'//char(0))
      write (ZW,'(//,"Enter input file name: ",$)')
      read (ZR,'(a12)') filename
      open (10,FILE=filename)
c
      read (10, '(f10.1)') freq                 ! radar freq
      read (10, '(f10.1)') antena               ! radar antenna ht
      read (10, '(f10.1)') rectar               ! receiver/target height
      read (10, '(a1)') polar                   ! antenna polarization
      read (10, '(a1)') antype                  ! antenna type
      read (10, '(f10.1)') bwidth               ! vert. beam width
      read (10, '(f10.1)') elevat               ! ant. elev. angle
      close(10)
c
      RETURN
      END
```

```
c
c  Subroutine sysinp
c
c  Subroutine SYSINP prompts the user for EM system parameters and re-
c  turns.  System parameters can be entered from the keyboard or from a
c  file.  If the system is entered from the keyboard it can be stored in
c  a file.
c
c  Variable:        Description:
c    atype         Antenna type:
c                    O - omnidirectional
c                    S - sin(x)/x
c                    C - cosecant-squared
c                    H - height-finder
c    beam          Beam width in degrees.
c    elang         Antenna pointing (elevation) angle in degrees.
c    fmhz          EM system frequency in MHz.
c    filename      EM system filename.
c    rectar        Receiver/radar target height, m.
c    plr           Antenna polarization:
c                    H - horizontal
c                    V - vertical
c                    C - circular
c    rectar        Receiver/target height, m.
c    xmtr          EM system antenna height, m.
c
c
      SUBROUTINE sysinp(FMHZ, XMTR, RECTAR, PLR, ATYPE, BEAM, ELANG)
c
c
      real*4 beam, elang, fmhz, rectar, xmtr
      character*1 atype, dummy, plr
      character*20 filename
      integer*2 ZW, ZR
c
c       Specify the read (5) and write (6) channel numbers.
      ZW = 6
      ZR = 5
c
c       Enter EM system parameters from file or keyboard.
      write(ZW,'("You may enter EM system from a file or keyboard.")')
      write(ZW,'("Enter EM system data from file? (yes or no) ",$)')
      read(zr,'(A1)')dummy
      IF ((dummy(1:1) .eq. 'y').or.(dummy(1:1) .eq. 'Y')) THEN
c       Enter EM system data from a file.
        call sysfil(fmhz,xmtr,rectar,plr,atype,beam,elang)
      ELSE
c       Enter the EM system parameters from keyboard.
        write(ZW,'("Enter EM System Parameters: ")')
c
c         Initialize EM system variables.
        fmhz = 5600.0
        xmtr = 25.0
        rectar = 25.0
        plr = "H"
        atype = "O"
        beam = 0.0
        elang = 0.0
c
        write(ZW,1010)
 1010   format('Enter frequency in MHz (100 to 20,000) ',$)
        read(ZR,*) fmhz
        IF (fmhz .LT. 100.0) fmhz = 100.0
        IF (fmhz .GT. 20000.0) fmhz = 20000.0
```

```
c
      write(ZW,1015)
 1015 format('Enter transmitter height in meters (1 to 100) ',$)
      read(ZR,*) xmtr
      IF (xmtr .LT. 1.0) xmtr = 1.0
      IF (xmtr .GT. 100.0) xmtr = 100.0
c
      write(ZW,1020)
 1020 format('Enter receiver/target height in meters (1 to 30000) ',$)
      read(ZR,*) rectar
      IF (rectar .LT. 1.0) rectar = 1.0
      IF (rectar .GT. 30000.0) rectar = 30000.0
c
      write(ZW,1025)
 1025 format('Enter EM system polarization (H, V, C) ',$)
      read(ZR,'(A1)') plr
      IF ((plr .EQ. "c") .OR. (plr .EQ. "C")) plr = "C"
      IF ((plr .EQ. "v") .OR. (plr .EQ. "V")) plr = "V"
      IF ((plr .NE. "V") .AND. (plr .NE. "C")) plr = "H"
c
      write(ZW,1030)
 1030 format('Enter antenna type - options are: Omnidirectional, '
     1 /,'Sin(x)/x, Cosecant-squared, Height-finder (O, S, C, H)) ',$)
      read(ZR,'(A1)') dummy
      IF ((dummy .EQ. "o") .OR. (dummy .EQ. "O")) atype = "O"
      IF ((dummy .EQ. "s") .OR. (dummy .EQ. "S")) atype = "S"
      IF ((dummy .EQ. "c") .OR. (dummy .EQ. "C")) atype = "C"
      IF ((dummy .EQ. "h") .OR. (dummy .EQ. "H")) atype = "H"
      IF ((atype .NE. "S") .AND. (atype .NE. "H") .AND.
     1     (atype .NE. "C")) atype = "O"
c
      beam = 0.0
      elang = 0.0
      IF(atype .NE. "O") THEN
        write(ZW,1035)
 1035   format('Enter antenna beam width in degrees (>0.0 to 45) ',$)
        read(ZR,*) beam
        IF (beam .LE. 0.0) beam = 0.10
        IF (beam .GT. 45.0) beam = 45.0
c
      write(ZW,1040)
 1040 format('Enter antenna elevation angle in degrees (-10.0 to 10.0)'
     1        /,'(0 is normal) ',$)
        read(ZR,*) elang
        IF (elang .LT. -10.0) elang = -10.0
        IF (elang .GT. 10.0) elang = 10.0
      END IF
      write(ZW,'("Do you wish to store this EM system in a file?",
     1 " (yes or no) ",$)')
      read(zr,'(A)')dummy
      IF ((dummy(1:1) .eq. 'y').or.(dummy(1:1) .eq. 'Y')) THEN
        write (ZW,'(" Current System Files: ")')
        call system ('ls [S]* 1>&2'//char(0))
        write (ZW, 1045)
 1045   format("Enter file name (First letter MUST be S): ",$)
        read (ZR,'(a12)') filename
        open (10,FILE=filename)
c
c     Write frequency and antenna heights in file.
        write(10, '(f10.1)') fmhz
        write(10, '(f10.1)') xmtr
        write(10, '(f10.1)') rectar
c     Write the antenna characteristics in file.
        write(10, '(a1)') plr
```

```
          write(10, '(a1)') atype
          write(10, '(f10.1)') beam
          write(10, '(f10.1)') elang
c           close file
          close(10)
        END IF
      END IF
c
      RETURN
      END
```

```
c
c  Subroutine tropo
c
c  Subroutine TROPO returns the troposcatter loss for a given range.
c  Troposcatter loss is based on models by Yeh with a frequency-gain
c  correction term, H0, from National Bureau of Standards Document
c  NBS 101.  Frequency gain factor gives additional loss for low
c  frequency, low-sited antennas.
c
c  VARIABLE:        DESCRIPTION:
c    ae           Effective earth radius in kilometers
c    exloss       Antenna gain for lowest optical region ray in dB
c    fcubed       Frequency cubed
c    horizn       Horizon range in kilometers
c    h1           Transmitter height in meters
c    h2           Radar target/receiver height in meters
c    h0           Frequency gain factor in dB
c    r            Ground range in km
c    rnsterm      Constant involving Surface Modified refractivity
c    rnsubs       Modified refractivity value at the sea surface
c    rone         4*PI*h1*ttot/wavelength
c    rtwo         4*PI*h2*ttot/wavelength
c    tfac         Troposcatter region constant
c    tloss        Troposcatter loss in dB
c    tsub0        Angle, theta sub 0, associated with total range r
c    tsub1        Angle, theta sub 1, associated with horizon range r1
c    tsub2        Angle, theta sub 2, associated with horizon range r2
c    ttot         Scattering angle, (theta in NBS 101)
c
c    various      All variables not listed above are temporary.  Most
c                   variables use the names given in NBS 101.
c
      SUBROUTINE tropo(r,tloss)
c
c
      real*4 chi, csub1, csub2, delh0, etas, horizn, hsub0,
     1       h0, h0r1, h0r2, q, r, rnsterm, rnsubs, rone, rtwo,
     2       s, tfac, tloss, tsub0, tsub1, tsub2, ttot, zeta
c
      include 'ffac.common'
      include 'envsys.common'
c
      rnsubs = Munits(1)
      tfac = 0.08984 / rk
      horizn = 3.572 * ( SQRT(rk * h1) + SQRT(rk * h2) )
      tsub0 = r / ae
```

```
      tsub1 = SQRT(h1 * ae/500.0) / ae
      tsub2 = SQRT(h2 * ae/500.0) /ae
      ttot = tsub0 - tsub1 - tsub2
      zeta = ttot/2.0 + tsub1 + (h1 - h2) / (1000.0*r)
      chi  = ttot/2.0 + tsub2 + (h2 - h1) / (1000.0*r)
      rone = h1 * 0.0419 * freq * ttot
      rtwo = h2 * 0.0419 * freq * ttot
      IF (rone .LT. 0.1) rone = 0.1
      IF (rtwo .LT. 0.1) rtwo = 0.1
      s = zeta / chi
      IF (s .GT. 10.0) s = 10.0
      IF (s .LT. 0.1)  s = 0.1
      q = rtwo / (s * rone)
      IF (q .GT. 10.0) q = 10.0
      IF (q .LT. 0.1)  q = 0.1
      hsub0 = s * r * ttot / (1.0 + s)**2
      etas = 0.5696*hsub0 * (1.0 + rnsterm*EXP(-3.8e-6 * hsub0**6))
      IF (etas .GT. 5.0)  etas = 5.0
      IF (etas .LT. 0.01) etas = 0.01
      csub1 = 16.3 + 13.3*etas
      csub2 = 0.4 + 0.16*etas
      h0r1 = csub1 * (rone + csub2)**(-1.333)
      h0r2 = csub1 * (rtwo + csub2)**(-1.333)
      h0 = (h0r1 + h0r2) / 2.0
      delh0 = 1.13 * (0.6 - ALOG10(etas)) * ALOG(s) * ALOG(q)
      IF (delh0 .GT. h0) THEN
        h0 = 2.0*h0
      ELSE
        h0 = h0 + delh0
      END IF
      IF (h0 .LT. 0.0) h0 = 0.0
      tloss = 114.9 + tfac*(r-horizn) + 10.0*ALOG10(r*r*freq**3)
      tloss = tloss - rnsubs*0.2 + h0 + exloss
c
      RETURN
      END
```

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A standard electromagnetic (EM) propagation model has been developed at the Naval Ocean Systems Center. It provides the user with a method of assessing the effects of the environment on the performance of microwave EM systems. The software implementation of the model is written in ANSI FORTRAN 77, with MIL-STD-1753 extensions. The program provides the user with the pattern propagation factor in decibels, as a function of range, when supplied with the proper environmental and EM system inputs. The modeled environmental effects include refraction caused by a multisegmented refractivity profile, sea-surface roughness caused by local winds, evaporation ducting, surface-based ducts caused by atmospheric layering, and tropospheric scattering. The program that implements the model can be either incorporated into an application model that requires EM propagation information or used as a stand-alone program.

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